APPENDIX B

PROBABILISTIC ANALYSIS OF THE POTENTIAL FOR BUILDING-WIDE FIRE IN PF-4

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PROBABILISTIC ANALYSIS OF THE POTENTIAL FOR BUILDING-WIDE FIRE IN PF-4

EXECUTIVE SUMMARY

This technical analysis consists of a re-examination of the plausibility of a building-wide fire at the Los Alamos National Laboratory (LANL) Plutonium Facility (PF-4) at TA-55 under the following hypothetical circumstances: (1) the propagation of a glovebox fire; and (2) fire from a severe site-wide earthquake. PF-4 is a Category 2 nuclear facility that has been in operation since 1978. The chemical and metallurgical processes conducted at PF-4 routinely involve hazardous chemicals and special nuclear material (SNM). These processes are carried out in gloveboxes that are located within various laboratory rooms in PF-4. Fire barriers are used to separate adjacent laboratory rooms, as well as the two building wings. Other design features are in place to help prevent fire propagation, including a dedicated automatic fire suppression system. The building structure, fire walls, and many other PF-4 items have been designed specifically or hardened to withstand a seismic event.

For the purpose of this study, a building-wide fire is defined as a fire large enough to encompass all PF-4 laboratory and basement areas and subject the entire building inventory of the plutonium material at risk to high temperatures. The overall objective of the analysis was to generate point-value estimates for the frequency of building-wide fires using conservative, bounding assumptions where necessary. By comparison, a “best-estimate” analysis, if performed, would attempt to eliminate conservative assumptions through additional studies and deterministic analyses. It was deemed reasonable that frequency estimates from the conservative, bounding analysis, together with engineering judgment, would form the basis for drawing conclusions related to “plausibility.”

This study was carried out in two parts. First, the PF-4 design features were compared with the codes and standards for design and operation of facilities having similar hazards. This design verification activity included extensive walk-downs of the PF-4 building. Results from the design verification provided valuable insights about the robustness of the PF-4 building and provided a means for analysts to ensure that the analysis would represent the present state of PF-4 operations accurately. In the second part of the study, a probabilistic analysis was performed to evaluate the initiation, growth, and propagation of fires at PF-4. The probabilistic analysis included an examination of how each safety feature would inhibit or prohibit fire propagation. The probabilistic analysis was based on established risk assessment methods that included the use of event- and fault-tree logic models. Results from the probabilistic analysis provided a quantitative measure of the relative effectiveness of each safety feature, as well as an estimate of the overall frequency of a building-wide fire at PF-4.

Deterministic computer models were developed and analyzed to evaluate various physical phenomena related to fire propagation. In selected instances, the analysis used simplifying but conservative modeling assumptions to address issues related to fire spread instead of performing complex analyses using nonstandard tools. For the seismic portion of the analysis, the entire site-specific seismic hazard curve was sampled instead of truncating the analysis at an arbitrary pre-set maximum level for ground motion. The probabilistic analysis used actual plant operational data to support quantification of the results.

Propagation of a glovebox fire into a building-wide fire is estimated to occur with a point-value frequency of $4x10^{-10}$/yr. Stated differently, this type of accident scenario would be expected to occur about 1 time in every 2.5 billion years. The frequency for this accident scenario is very low because of a combination of fire mitigation factors and design features, including an automatic fire suppression system, limited and monitored amounts of combustible materials in laboratory rooms, and robust fire barriers. Several very conservative assumptions were used in this portion of the analysis. For example, even though there have been no instances of laboratory room or basement fires at TA-55, the analysis assumed that a room fire would occur with the same frequency as a glovebox fire. Furthermore, the frequency of a glovebox fire was based conservatively on some events that were not actual glovebox fires, but were instead only precursor events having a low potential to ignite a fire. Also ignored was the fact that glovebox fires will often self-extinguish because of the relatively small amount of combustible materials typically present in gloveboxes. In addition, no credit was taken for the response and mitigating actions of dedicated, off-site fire department personnel.

The analysis of building-wide fire from a severe site-wide earthquake produced two scenarios of interest. The first scenario involves a seismic-induced fire that spreads throughout an entire wing as a result of failure of the fire suppression system or interior fire walls. Seismic-induced failure of the H-wall crossover dampers subsequently allows the fire to spread to the other wing, resulting in a building-wire fire. The frequency of this scenario is estimated to occur with a point-value frequency of $4x10^{-6}$/yr. The second scenario involves the collapse of the building as a result of the seismic event. The frequency of this scenario is estimated to be $5x10^{-6}$/yr. Stated differently, these accidents would be expected to occur once every 500,000 yr. It was assumed in these calculations that fire spread would be independent of the operational status of the ventilation system even though some calculations suggest that the ventilation system would have to remain operable for fire to spread.

In summary, a conservative bounding analysis has demonstrated that a building-wide fire is unlikely to occur during the life cycle of PF-4. A "best-estimate" analysis, if performed, would provide the basis for further judgment into the degree of conservatism inherent in many of the analysis assumptions. Elimination or relaxation of conservative assumptions, in turn, would reduce the point-value frequency estimates of a building-wide fire.

1.0. INTRODUCTION

1.1. Background

Construction and Operation of PF-4 Facility

The Plutonium Facility (PF-4) at LANL, TA-55 is a Category 2 nuclear facility that has been in operation since 1978. The chemical and metallurgical processes conducted at PF-4 routinely involve hazardous chemicals and special nuclear materials. The PF-4 building is broadly divided into two wings separated by a 3-hour (3-hr) fire-rated[1] concrete wall called the "H-Wall" (see Fig. 1-1). Each wing is formed of two areas that in turn are formed of a strip of laboratory rooms. Each of the 100, 200, 300 and 400 Areas has its own dedicated heating, ventilation, and air conditioning (HVAC) system equipped with intake and exhaust high-efficiency particulate air (HEPA) filters. Laboratory room walls, floors, and ceilings are constructed of 2-hr-rated fire barrier materials to provide qualified fire isolation from the adjoining rooms, the attic, and the basement. The laboratory room doors are constructed of 1.5-hr-rated fire barrier materials. In addition, each room is equipped with manual (e.g., A/B/C fire extinguishers) and automated (wet pipe 212^{o}F fire sprinklers and Halon) fire suppression systems. The fire sprinklers are supplied with water by a dedicated fire water supply system (FWSS) with on-site water tanks and redundant fire pumps. In addition, each laboratory room has central and local fire alarms to alert operators of possible fires. The PF-4 building perimeter walls serve as the ultimate confinement barrier against uncontrolled release of material at risk (MAR), whereas the laboratory room boundary forms a "qualified" fire barrier against propagation of fire within the building. By design, the PF-4 structure, HEPA filter plenums, and the associated HVAC ductwork will withstand the effects of an evaluation-basis event (EBE) earthquake with 0.3-g peak horizontal acceleration. Through various engineering analyses, it has been established that the interior walls, ceilings, and floors have a high confidence and low probability of failure (HCLPF)[2] at 0.5 g, whereas the perimeter walls and the H-wall have a HCLPF of almost 0.8 g.

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[1] The fire rating is based on the National Fire Protection Association (NFPA) design criteria for fire barriers. The construction details of these walls are provided in Sec. 2 and Appendix-B.

[2] An HCLPF of 0.5 g implies that at a mean ground acceleration of 0.5 g, that structure has a failure probability of 10^{-2} with 95% confidence. Structural experts made such a determination based on experimental simulations and modeling activities.

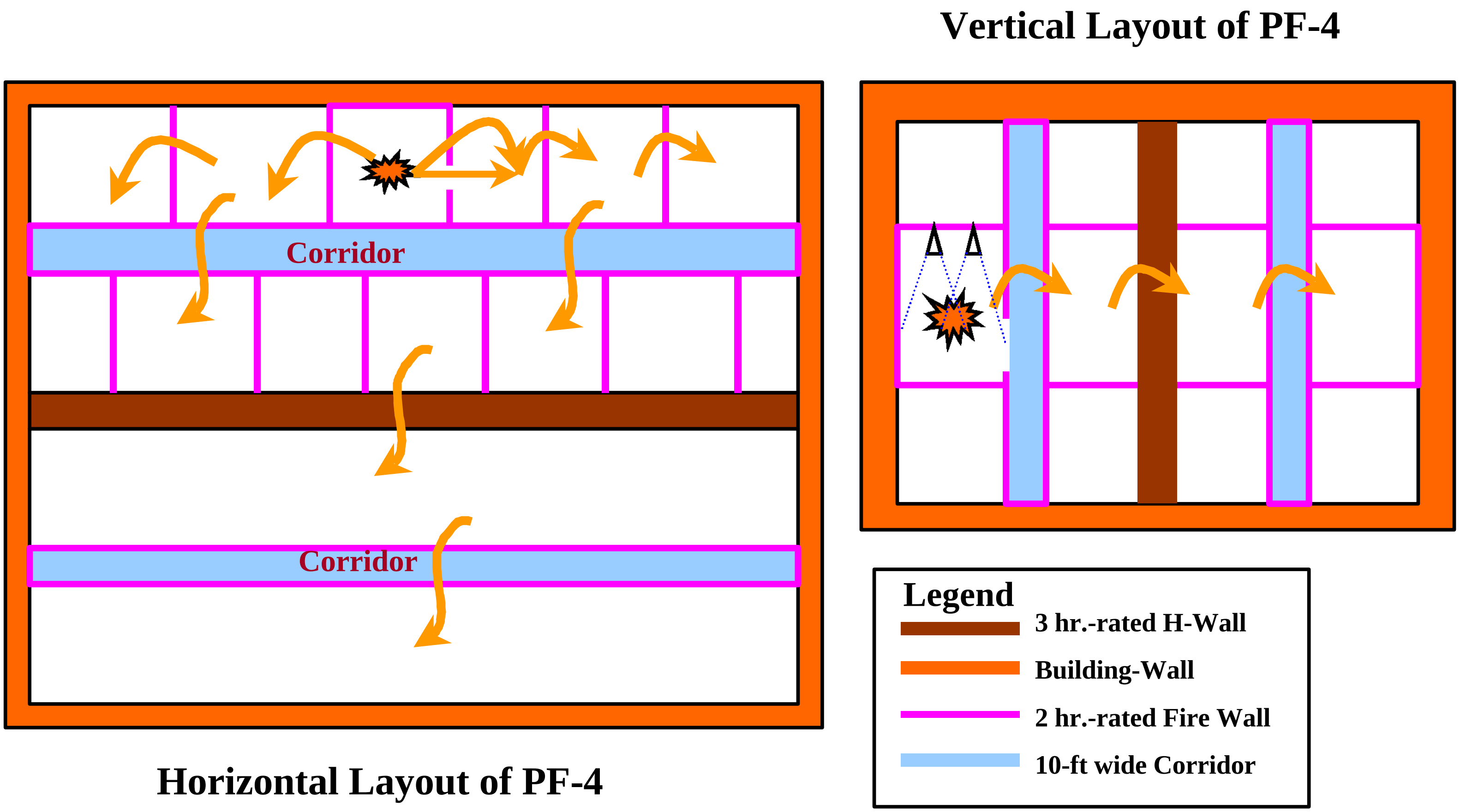

Fig. 1-1. Layout of PF-4 Building.

Each laboratory room contains numerous seismically qualified gloveboxes in which all operations involving hazardous materials (including their storage) are undertaken. A glovebox is typically a leak-proof, enclosed steel structure with noncombustible glass windows and ports cut out for housing rubber gloves. The glovebox forms the primary confinement. MAR is stored in special containers within the glovebox to minimize release in the event of fire or seismic event.[3] At any given time, a majority of the gloveboxes is very sparsely used, and they contain few (if any) combustible materials. The gloveboxes in which significant quantities of nuclear MAR, pyrophoric materials, or heat sources are processed (or stored) have the following additional safety features.

1. They are inerted.[4]
2. They are specially braced to withstand beyond-evaluation-basis earthquakes.[5]
3. They are equipped with heat detectors and alarms.
4. They have dedicated exhaust HEPA filters.
5. They have certain controls on the type, form, method of storage, and amount of combustible (or pyrophoric) materials that can be stored inside.

To minimize fire risk, administrative controls are placed on the quantity of transient combustible materials (in terms of equivalent cellulose pounds per square foot) permissible in a laboratory room and the storage of combustible gases. Biweekly surveys of the location and quantity of combustible materials in PF-4 (covering the entire year of 1998) clearly established that transient combustible loads in most of the PF-4 laboratory rooms are far below 1/2 lb/ft^2. The combustible gasses (e.g., hydrogen and methane) are permitted within the building in small quantities and are stored in high-pressure 1-L gas cylinders at 2250 psig. These limited volumes do not present a flammability hazard if they are released to the rooms accidentally.

Further details on the PF-4 construction and safety systems are provided in Sec. 2 and in the Updated Final Safety Analysis Report (FSAR).

FSAR Accident Analysis

The FSAR identified a set of credible accidents, referred to as the evaluation-basis accidents (EBAs) and analyzed them systematically to quantify their on-site and off-site consequences. These accidents were selected based on detailed hazard analyses performed for each process underway at TA-55. The following fire and seismic accidents are analyzed in the FSAR.

1. **Operational Accident: Laboratory Fire in the Heat Source Production Area.** This accident represents various scenarios of Laboratory Room or Glove Box fires that breach glovebox confinement followed by loss of active ventilation.
2. **Operational Accident: Ion Exchange Column Thermal Excursion.** This accident covers various scenarios that result in explosion induced release of MAR due to a glove box breach.
3. **Natural Phenomena: Earthquake.** This accident evaluated the potential effects of an earthquake with a mean peak horizontal acceleration of 0.3 g on PF-4. The earthquake is modeled to cause free fall spill of MAR into the laboratory rooms, followed by failure of the ventilation system. Although secondary fires are possible, they were screened out because they would be small and their effects would be bounded by other seismic event assumptions.
4. **Operational Beyond-Evaluation-Basis Accident (BEBA).** Fire in the Heat-Source Production Area. This is a more severe version of the fire scenario described above.

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[3] Powders and liquids are stored in screw-top, thick-steel-pipe containers. Metals and pellets are stored in press-on containers. These containers currently are being upgraded.

[4] "Inerted" is a word used to describe a glovebox in which air is purged from the interior volume and replaced with gases such as nitrogen and argon that do not support combustion. Such gloveboxes are isolated from the neighboring gloveboxes and equipped with oxygen monitors and alarms.

[5] Independent studies by Los Alamos scientists and outside experts have concluded with high confidence that a majority of the gloveboxes will withstand a design-basis earthquake (0.3 g). The high-risk gloveboxes are being braced to withstand beyond-design-basis earthquakes (between 0.4 and 0.5g).

5. **Natural Phenomena Beyond-Evaluation-Basis Accident (BEBA): 0.5-g Earthquake.** This accident examines increase in risk associated with a 0.5-g earthquake at TA-55.

The results of the analyses were instrumental in identifying the safety-class structures, systems, and components (SCSSCs) and safety-significant structures, systems, and components (SSSSCs) that would be required to mitigate accident progression and limit public and worker consequences. These results were used later in the LANL Site-Wide Environmental Impact Statement (SWEIS), and the Storage and Disposition of Weapons-Usable Fissile Materials Programmatic Environmental Impact Statement (PEIS) as needed.

1.2. Scope and Objectives of the Present Study

The overall objective of this study is to examine the “plausibility” of a building-wide fire at TA-55 under the following hypothetical circumstances: (1) the propagation of a glovebox fire and (2) fire resulting from a severe site-wide earthquake. For the sake of this study, a “building-wide” fire is defined as a fire large enough to encompass all four areas of the PF-4 building (i.e., 100, 200, 300, and 400 areas) and subject the entire building inventory of MAR to high temperatures. The primary focus of the study was to conservatively estimate the frequency of a building-wide fire at PF-4 with the understanding that the frequency estimates together with engineering judgement can be used to draw conclusions related to “plausibility.” The study would quantify the frequency after taking into consideration the process modifications that are necessary for pit manufacturing.

This study was carried out in two parts. The first part involved comparing the PF-4 design features with the codes and standards for design and operations of facilities of similar hazards—both government and civilian facilities. This process of design verification also included extensive walk-downs of the PF-4 building by the analysts to ensure that PF-4, as analyzed, accurately reflects the present state in which it is being operated. The results of this part of the analysis provided valuable insights regarding the robustness of the PF-4 construction. The second part of the analysis involved a systematic evaluation of fire initiation, growth and propagation at PF-4. This evaluation examined how each mitigating system (or barrier) would inhibit fire propagation, and coupled that information with the probability for failure of each mitigating system to quantify the cumulative frequency (or likelihood) of a building-wide fire. Event trees and fault trees were used to integrate the probabilistic results with the accident progression. This approach provided a “quantitative” measure of the relative effectiveness of each safety feature, as well as the overall frequency of a building-wide fire at PF-4.

This study evaluated the frequency for a building-wide fire as an outgrowth of two initiators: (1) an operational accident, a small local fire[6] initiated in a laboratory room, and (2) natural phenomena, a fire resulting from an earthquake. The study modeled existing mitigating systems and gloveboxes in their present configuration.[7] Established computer models were used to establish the effect of a mitigating system’s failure/deficiency on fire propagation, for example, failure of fire sprinklers. Where necessary, simplifying and conservative modeling assumptions were adopted in lieu of performing complex analyses using nonstandard tools. On the probability front, actual plant operational data were used to derive initiator frequency as well as mitigating systems component failure probabilities. For seismic events, this study sampled the entire seismic hazard curve instead of truncating the analysis at any preset maximum. The overall outcome of the study is a numerical point estimate of the frequency of a building-wide fire.

1.3. Applicability and Limitations

This study was oriented primarily toward quantification of frequency (or plausibility) of a building-wide fire at PF-4. In other words, the accident sequence of interest is propagation of a small fire throughout the building. Very little effort was devoted to best-estimate quantification of the likelihood or consequences of sequences resulting in limited damage to the facility. Such sequences are addressed in the PF-4 SAR. Therefore, the results of this analysis should not be used to draw conclusions regarding any issues other than the likelihood of a building-wide fire.

As with any engineering study of complex facilities, several simplifying assumptions were made to limit the complexity of analyses to be performed. Therefore, the results of this study should not be taken out of context. For

[6] An example of such a fire is spontaneous ignition of alcohol-soaked rags located in a glovebox.
[7] It is assumed that the present system configuration will not change substantially for pit fabrication.

example, this study did not undertake detailed analyses related to conditions required for a small glovebox fire to grow into a larger laboratory room fire. Instead, the study assumed that all glovebox ignitions, irrespective of their size and local combustible loads, would grow to be a laboratory room fire if not immediately attended to by laboratory workers. This assumption is very conservative because at the low glovebox combustible loads that are typical of PF-4, small glovebox fires would likely self-extinguish. Therefore, the frequency estimates for laboratory room fires are very conservative. This conservatism is ultimately reflected in the estimates for the frequency of a building-wide fire.

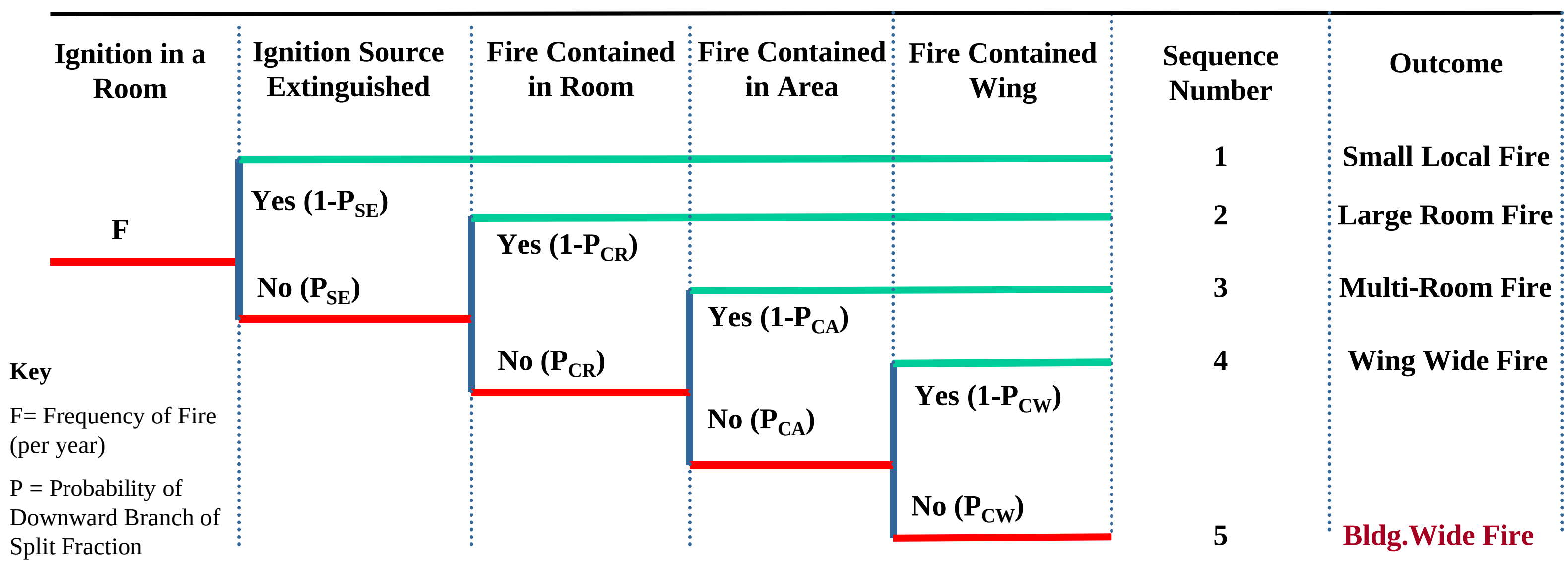
1.4. Report Outline

The technical analysis is presented in Secs. 25. Section 2 presents an overview of the probabilistic risk assessment methodology used to estimate the frequencies. Section 3 presents the results of a building-wide fire resulting from an operation fire. Section 4 presents the results of a building-wide fire resulting from a seismic event, and finally Sec. 5 presents the conclusions of this report.

2.0. OVERVIEW OF THE METHODOLOGY

Fire propagation within the PF-4 building was evaluated probabilistically by developing and analyzing an event/fault-tree logic model. An event tree is a graphical model that portrays various possibilities for the progression of an accident. Figure 2-1 is a generic event tree that describes the progression of an operational fire in PF-4. The event tree is structured so that the progression of the accident is represented in a time-ordered manner from left to right. The event tree contains a set of "event headings," the first of which represents the initiating event (e.g., glovebox fire), whereas the subsequent headings represent post-initiator events that may or may not occur in the accident progression (e.g., fire contained in the laboratory room). The last heading on the event tree (far right) represents the outcome of the accident (e.g., Small Local Fire). The post-initiator events represent the success or failure of various mitigating systems/features that are designed to contain fire during that phase of propagation. Separate pathways through the tree, which flow from the left to right, represent the various possibilities for accident progression. These pathways are referred to as "Accident Sequences" and are usually identified by a name or number. "Success" of a post-initiator event is delineated by the pathway branching upward, failure is shown by the pathway branching downwards, and no effect is shown by not branching. In Fig. 2-1, for example, Accident Sequence 2 represents a fire (initiating event) that was not extinguished promptly but was contained in the room of origin. The outcome was a small local fire.

The accident-sequence frequency is quantified by multiplying the frequency of the initiating event (for example, the number of fires per year) with the failure/success probabilities (split fractious) of each post-initiator event associated with that sequence. For example, in Fig. 2-1, the **failure** probability under each intermediate event is the estimated probability that mitigating systems associated with that event would **not** function properly and extinguish the fire. The success probability is a complement of the failure probability (≈ 1-Failure Probability). These failure probabilities are calculated using fault-tree models that model various faults in each item or component of the associated mitigating systems that would render them inoperable. Each fault is quantified with a numerical probability of occurrence derived from PF4-specific operational history as well as external data sources. These



Calculation of Sequence Frequencies

Sequence 1: Frequency = $F*(1-P_{SE})$

Sequence 2: Frequency = $F*P_{SE}*(1-P_{CR})$

Sequence 3: Frequency = $F* P_{SE}*P_{CR}*(1-P_{CA})$

Sequence 4: Frequency = $F* P_{SE}*P_{CR}*P_{CA}*(1-P_{CW})$

Sequence 5: Frequency = $F* P_{SE}*P_{CR}*P_{CA}*P_{CW}$

Fig. 2-1. Event tree representing progression of an operational fire in PF-4.

faults are combined in a logical manner so that when solved, the fault-tree model yields an estimate of the failure probability of each post-initiator event.

The event-tree quantification process used in this study consisted of four major steps, which are shown in Fig. 2-2. These steps and their outcomes are described briefly below with the results and discussions provided in Secs. 3 and 4.

2.1. Selection of Initiating Events

A major objective of this study is to estimate the frequency with which a fire initiated by either (a) a glovebox fire or (b) a severe site-wide earthquake spreads to engulf the entire PF-4 building. The first element of the study is to estimate the frequency with which glove box fires occur, and to estimate the frequency of an earthquake of sufficient magnitude to start a fire in the PF-4 building. The methods used to develop these initiating event frequencies are explained below. The methods used to characterize the companion probabilities that either of these categories of fires would spread to the entire building are described in subsequent sections of this report.

Operational Fire: A Small Local Fire Initiated in a Laboratory Room

A typical example of an operational fire at TA-55 would be spontaneous ignition of a pile of alcohol-wetted and ^{238}Pu-contaminated rags stored in a glovebox. Operational history suggests that such events are rare because contaminated rags are stored in gloveboxes only for a brief period of time at PF-4 (and never in gloveboxes that also have other flammable materials or MAR). Furthermore, every incident of glovebox fire in the past was either

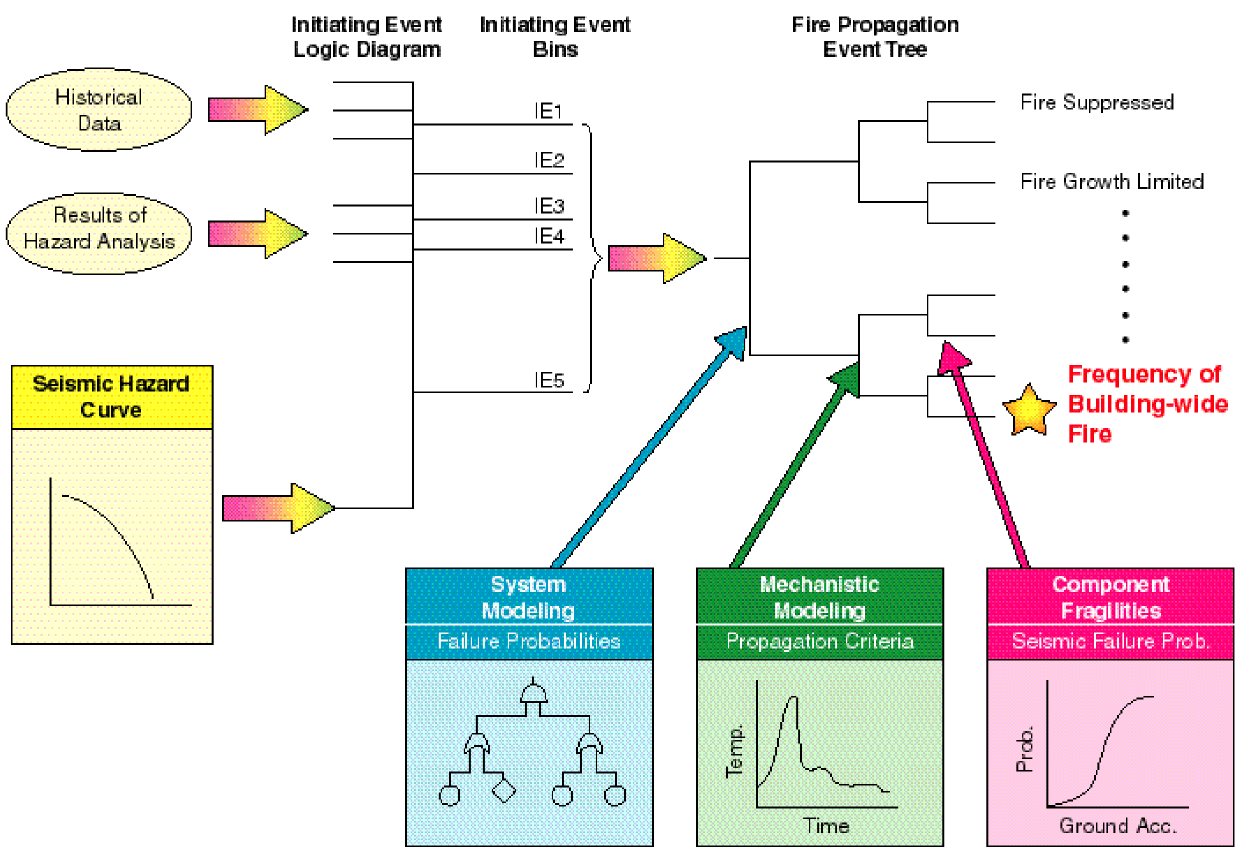


Fig. 2-2. Overview of analysis methodology.

extinguished immediately by a TA-55 worker or self-extinguished because of the small quantity of combustible material involved. Nevertheless, if one were to postulate that as a result of human error, rags were left in a glovebox that contains large inventories of fast-burning flammable liquids, then rapid fire growth could result. Leonard (1999) provides descriptions of analyses undertaken to model various steps involved in the progression of a glovebox fire. Most of the gloveboxes possess such small quantities of combustibles that the hot gases from the fire would be vented off easily by the HVAC system, resulting in an insignificant increase in glovebox temperatures. However, if the combustible loads are sufficiently large the combustion products together with radiant heat transfer can breach the gloves (either burn through them or overpressure them). In turn, escaping hot gases may ignite flammable materials located outside the glovebox. This would result in a small local fire in a region close to the glovebox. Alternately, the fire may start in the laboratory room as a result of human error and/or as a result of other precursors identified in the hazard analyses. The analyses conducted as part of this study demonstrated that irrespective of the location where the fire initially starts (i.e., inside or outside the glovebox), pathways for fire growth are essentially same. As a result, it was decided to merge these two initiating events into a single event, "operational fire" and analyze them together.

Operational fire is not expected to affect any of the mitigating systems such as the fire suppression system or HVAC. However, it is assumed that possible release of radioactivity into the laboratory room may limit TA-55 worker response except for an initial few minutes.

Natural Phenomena: A Fire Resulting from a Severe Earthquake

The TA-55 FSAR addressed the mechanical release of MAR as a result of evaluation-basis and beyond-evaluation-basis earthquakes. This study analyzed the potential for fire as a result of seismic activity and subsequent fire propagation.

A postulated severe site-wide earthquake could lead to failure of several gloveboxes depending on the magnitude of the earthquake and the relative strength of each glovebox. The glovebox seismic failure mechanisms can vary from interruption of inert gas flow to the gloveboxes, where pyrophoric materials are stored, to toppling of gloveboxes in which ignition sources (e.g., a furnace) are operated/stored. The extent to which a glovebox is damaged depends on its fragility and the magnitude of earthquake. In either extreme, postulated failure may lead to ignition located either within the glove box or in the close proximity of the glovebox. Mechanistic determination of the exact criterion for initiating a fire following a seismic event is very complex and would involve major assumptions regarding the PF-4 manufacturing processes. For the sake of simplification, it was assumed conservatively that a seismic event powerful enough to "fail" a glovebox would result in ignition provided that the glovebox contains sources of ignition[8] (e.g., furnaces) or is used to store pyrophoric materials.

The seismic events are assumed to cause a loss of off-site electrical power, which would affect the HVAC and FWSS performance negatively.[9] Additionally, it would limit the response of both the TA-55 workers and the fire department staff. Severe earthquakes also may introduce large-scale cracks in the room walls and roof that can act as penetrations.

2.2. Systems Analyses

The PF-4 facility Systems Description Document (SDD), FSAR, and hazard analysis (HA) were reviewed to gather information regarding active and passive systems available for mitigating various accident sequences. This information was supplemented by facility walkdowns and personnel interviews.[10] For each system listed below, the information compiled included the system design, its present configuration, procedures for testing and maintenance, deficiencies or vulnerabilities, failure rates, and anticipated human response. This information was used to develop the fault trees for each system [see Darby (1999)]. To validate these models, underlying assumptions and the results of the fault tree analyses were discussed with the facility operators.

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[8] No attempt was made to estimate the probability that the heat source would be operational when the earthquake occurs.

[9] TA-55 also has an on-site, backup power supply that, if available, could be used to power the FWSS. While a seismic event of sufficient strength could also fail this backup power supply, the FWSS piping is less resistant to seismic events. Thus, a seismic event sufficiently strong to fail the backup power supply would also fail the FWSS.

[10] One registered fire protection engineer and two PRA experts were involved in the walkdowns.

Passive Barriers

The following passive barriers were modeled in the study.

1. The walls, ceiling, and floor of every laboratory room are constructed of 4-in.-thick gypsum wallboard that meets the National Fire Protection Association (NFPA) criterion for 2-h fire barriers. These firewalls have a HCLPF of 0.5 g. Typically, every room has one or two doorways connecting it to the adjoining room and the corridor. These doors are normally closed and meet the NFPA criterion for a 1.5-h fire barrier. A walkdown of the PF-4 facility revealed that small penetrations exist in the room walls and that gaps in the doorway may leak at high pressures. A typical example of a penetration is sealed electrical conduit. As shown in Bartlein (1999), such penetrations were found to have an insignificant effect on fire propagation. The success criterion for containing fire within the laboratory room was derived conservatively assuming that room doors will remain open throughout the accident.
2. A 10-ft-wide corridor separates each Area from the adjoining Area (100 from 200 and 300 from 400). The corridor is kept free of combustible materials at all times. This separation ensures that no continuous fuel train connects the adjoining areas. Deterministic analyses have shown that corridors are not very effective at containing hot combustible gasses emanating from the area under fire to ignite flammable materials in the adjoining area. This pathway for fire propagation was modeled in the study.
3. A 2-ft-thick concrete wall (H-wall) separates the north and south wings, which meets the NFPA requirements for 3-h fire separation. It has a HCLPF of 0.6 g, at which point large cracks and penetrations could develop in the wall. However, the HCLPF for catastrophic failure is 0.7 g. There are five penetrations in the wall. There are two sets of access doors in the upper level and two sets of access doors in the basement. These doors are normally closed and are equipped with automatic closure mechanisms (fusible links) that would close them when the nearby temperature exceeds 212^{o}F. The other penetration is a 4-ft x 7-ft trolley crossover line that also is equipped with a fusible link fire closure mechanism. This study quantified the probability associated with failure to close these penetrations and analyzed their effect on fire propagation.

Active Systems

The following active systems were modeled in this study.

1. ***Fire Sprinkler System.*** The PF-4 facility is fully protected by wet-pipe fire sprinkler systems. The FWSS, which feeds the sprinklers, consists of two independent ground-level storage tanks located remotely from each other. Each tank supplies a pump house containing one electric-driven, and one diesel-driven fire pump. Each of the four pumps is capable of supplying the demand of the fire sprinkler systems. Both pump houses supply water to the sprinkler system via a dedicated fire loop around the PF-4 facility. The fire loop, tanks, and pump houses have a HCLPF of 0.5 g. However, some of the sprinkler pipe hangers inside the PF-4 building have a HCPLF of 0.3 g.

2. ***HVAC System.*** The PF-4, Zone II, HVAC design uses a cascading scheme maintaining airflow from areas of low probability of contamination to areas of higher probability of contamination. Air enters the basement, from the outside through HEPA-filtered inlets, is distributed to the upstairs corridors, flows into the laboratory spaces, and is pulled into the basement plenum where approximately 10% of the air is exhausted through HEPA filters to a monitored stack. The building is maintained at a negative pressure with respect to the environment. This system, if operational during a fire, would lower laboratory room temperature, thus minimizing potential for flashover. On the other hand, during the late stages of accident progression, the HVAC may aid flashover by aiding in the distribution of hot gases.

   The PF-4, Zone I, HVAC design draws air from the basement, through HEPA filters, through the gloveboxes, and exhausts 100% of the glovebox air through HEPA filters, to the monitored stack. The glovebox lines are always maintained at a negative pressure with respect to the laboratory rooms.

Administrative Controls

The only administrative control taken credit for in this model is the transient combustible loads program. The findings from this program (which includes monthly walkdowns) were used in this study to establish probable fuel loadings within each laboratory room in PF-4. The program is implemented as a Technical Safety Requirement (TSR) for the facility and is under the control of a fire protection engineer. The transient fuel loads were added to the fixed combustible fuel loads (e.g., PMMA shields) to obtain room total fuel loads. The rooms with the highest fuel loading are 207, 208, and 209, primarily because of the PMMA shielding on the gloveboxes. The remainder of the facility maintains exceptionally low combustible loads (most < 0.5 lb/ft^2), which would limit fire propagation.

Human Response

The only human response taken credit for in this study involved a TA-55 worker extinguishing an operational fire during an early stage. In the model, for the worker to extinguish the fire (a) the worker must be present when the ignition occurs and (b) the worker is trained and equipped to undertake fire fighting. Operational history has shown that TA-55 worker intervention is a very effective means for containing fire. However, this study assigned a low probability for workers being successful at containing (or extinguishing) fires (24% for operational fires and 0% for seismic fires). The study did not give any credit for Los Alamos Fire Department response or the late response of TA-55 workers. Thus, the study assumptions regarding human response are very conservative.

2.3. Deterministic Modeling

Deterministic models were used to evaluate the pathways by which a TA-55 fire could ultimately propagate throughout the remainder of the PF-4 building, thereby resulting in a building-wide fire. Two computer codes were used in this analysis, *CFAST* and *MELCOR*. *CFAST* was used to model fires in large PF-4 enclosures, specifically laboratory areas/rooms and the building basement. *CFAST* is a zone model capable of predicting the environment in a multicompartment structure subjected to a fire. It calculates the time-evolving distribution of smoke and fire gases and the temperature throughout a building as a result of a postulated fire. *CFAST* was developed and verified by the National Institute of Standards and Technology and is recognized in the fire protection community. A registered fire protection engineer performed the *CFAST* calculations for PF-4. The *CFAST* calculations postulated fires of different severities and analyzed their response to the operation of various mitigating systems. The mitigating systems modeled included fire barriers (with and without penetrations), the fire sprinkler system, and the HVAC. These analyses were conducted based on very conservative assumptions regarding flashover and fire propagation.

The *MELCOR* computer code was used to model fires in small, interconnected compartments in PF-4, such as glove box lines. *MELCOR* has the capability of modeling HVAC and gas flows to a high degree of fidelity. *MELCOR* is an engineering-level computer code developed and verified by the US Nuclear Regulatory Commission (NRC) that models the progression of accidents in light-water reactor nuclear power plants. The *CFAST* and *MELCOR* analyses and associated results are described in detail in References 1 and 3. Figure 2-3 shows all fire propagation pathways modeled in the study and the barriers in place to prohibit propagation. The major findings from these analyses are as follows.

The physical construction of the glove box system in PF-4 (including the trunklines, drop boxes, etc.) is such that the events that occurred during two major glove box system fires at the Rocky Flats Plant could not occur at TA-55. The walls of the conveyor system (and all other boundaries of the glove box lines) in PF-4 are made of stainless steel, not the flammable Plexiglas/Benelex material used at Rocky Flats. Consequently, propagation of a fire that originates in a single glove box to other locations in PF-4 is conceivable under only two conditions:

1. Flame propagation along a continuous train of <u>transient</u> combustible material (e.g., temporary storage of trash or other combustible materials in glove box trunklines); or
2. Transport of hot combustion gases to other locations, causing ignition of combustible materials elsewhere in the system (i.e., flashover).

While the first condition is not precluded by current facility operating procedures, normal facility housekeeping practices include packaging and removal of residual, combustible materials from glove box lines, particularly those with active processes.[11]

Calculations performed to address the second condition [see Leonard (1999)] indicate propagation of a fire originating in a single glove box to other critical locations, such as neighboring glove boxes, drop boxes or

[11] Implicitly, fire propagation by means other than flashover are ruled out because (a) PF-4 walk-downs and surveys did not reveal a single instance where there were continuous fuel trains in a room or between gloveboxes and (b) the radiant heat flux is not sufficient to ignite materials not physically connected.

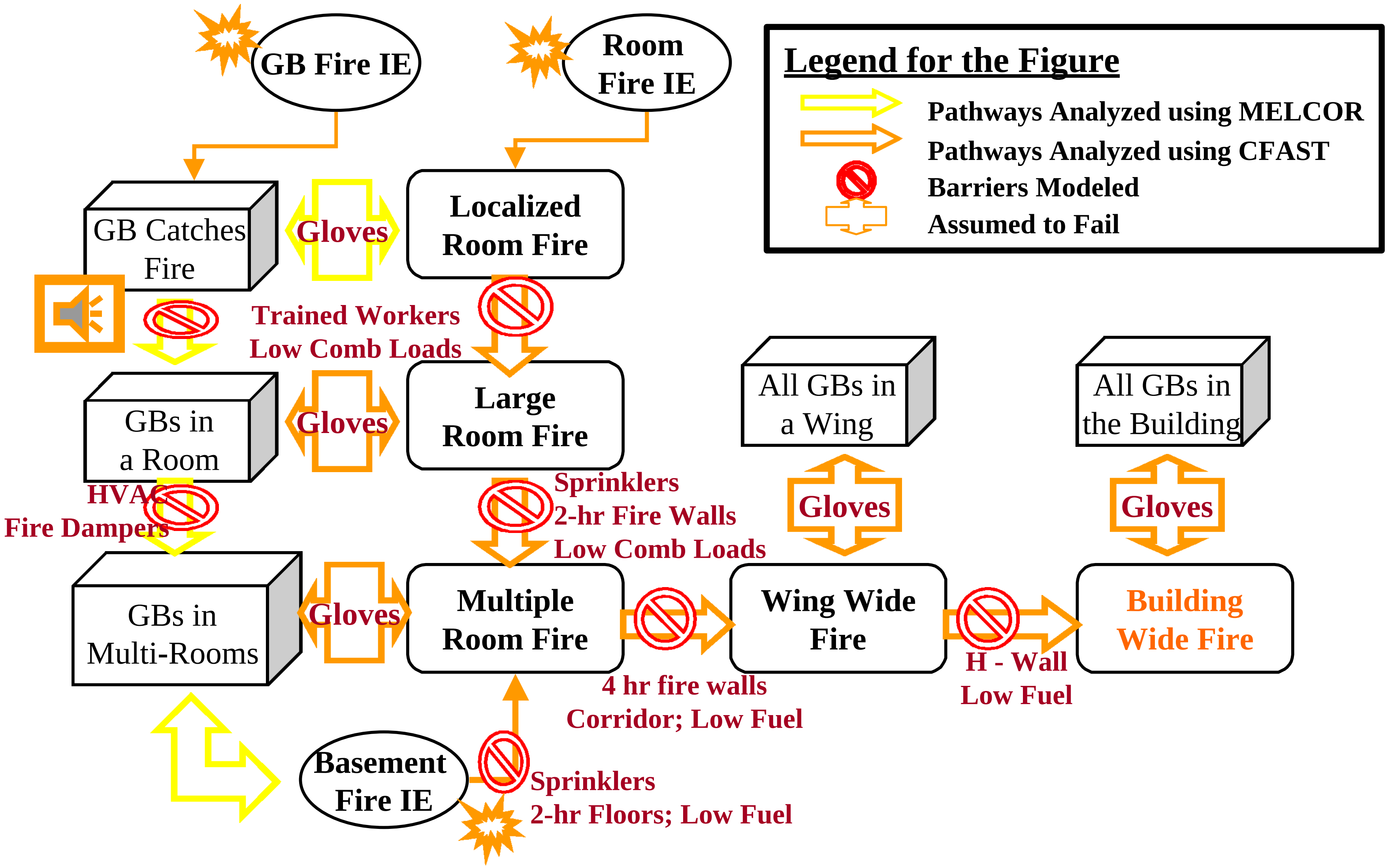


Fig. 2-3. Pathway and barriers to fire propagation.

ventilation system exhaust plena is extremely unlikely. Even under conditions in which engineered safety systems are postulated to fail (e.g., glovebox ventilation or drop box fire dampers), temperatures at any location other than (perhaps) highly localized regions of the room containing the glovebox were found to be well below values that would cause ignition of other combustible materials.

A small room fire[12] can propagate into local gloveboxes or grow to become a larger laboratory room fire if the TA-55 worker fails to extinguish/control the fire **and** the combustible loading is sufficient to cause flashover.[11]

A large laboratory room fire will actuate the 212°F sprinklers and heat sensors and will be contained if the FWSS systems function properly. If the sprinkler system fails, such a fire can breach the room fire walls provided sufficient combustible loads exist in the laboratory room. One of the mechanisms available for propagation generally is referred to as "flashover" and relates to the process by which hot combustion gases produced in the room will escape through the open penetrations and doorways and build up high temperatures in the adjoining room. The other mechanism relates to thermal failure of fire barriers because of overheating, i.e., when they are heated for periods longer than 2 h or when flame temperatures exceed the design temperature. Both these mechanisms can ultimately lead to ignition of flammable materials located in the adjoining room. CFAST was used to define the conditions under which room-to-room fire propagation would occur.

The understanding gained regarding various pathways for available fire propagation was instrumental in developing the event trees (i.e., the event trees were structured to reflect the insights gained from the modeling effort). The results of the modeling effort also were used to determine minimum set of systems and human actions that are necessary to contain/extinguish a fire at each phase of the accident progression. These results also were used to devise the logic by which individual system models (i.e., fault trees) are linked together to estimate sequence frequencies.

2.4. Accident-Sequence Quantification

This study developed two event trees, one each for operational fire and seismic fire. System fault trees were used to estimate the failure/success probabilities of the branch points (split fractions) on the event tree. The built-in logic for event-tree/fault-tree linking ensured that common-cause failures and system dependencies were handled accurately (e.g., a seismic event will take out electrical fans in the HVAC). The event- and fault-tree models were developed, quantified, and analyzed using the *SAPHIRE* computer code developed by the Idaho National Engineering Laboratory (INEL) for the NRC.

Operational history specific to TA-55 was used to derive initiating event frequencies and fault tree event probabilities. These data were supplemented, where necessary, by other available data sources.

3.0. BUILDING-WIDE FIRE RESULTING FROM OPERATIONAL FIRE IN A LABORATORY ROOM

The initiator considered in this section is an operational fire, which is defined as ignition either in or outside the glovebox. The potential for its propagation ultimately resulting in a building-wide fire is analyzed in this section. Supporting analyses for the results summarized in this section are presented in References 1 through 3.

3.1. Quantification of Initiating-Event Frequency

Various sources of historical data were reviewed to estimate the frequency of occurrence of random (operational) fires in the TA-55 building. Historical data specific to TA-55 were used where possible and were supplemented as necessary with data from other nuclear facilities. These estimates were compared with data derived from the operational histories of other DOE laboratory facilities (including Rocky Flats).

Historical data specific to TA-55 were derived primarily from Unusual Occurrence Report (UOR) events. UORs are generated for a variety of off-normal conditions or situations, for example, loss of glovebox integrity, spills, leaks, equipment failures, human errors, explosions, and fires. UOR events were gathered from various

[12] It is assumed that a small laboratory room fire will not trigger the sprinkler system until it grows to become a larger fire. It may trigger heat sensors and alert operators.

sources, including DOE's Safety Performance Measurement Systems (SPMS) database, DOE's Occurrence Reporting and Processing System (ORPS), a set of pre-ORPS data, and various TA-55 internal memoranda from 1981 and 1983. The earliest events contained in this set of data occurred in 1981. It is noteworthy that the incident history before implementation of the Pre-ORPS database in September 1990 may be incomplete. Table 3-1 lists all the fire-related events extracted from these data sources that pertain to TA-55.

Ignition Outside the Glovebox

Given the information from the preceding set of UOR data, there have been no occurrences of an ignition in a PF-4 laboratory room outside the glovebox. The primary reasons for such a low frequency are (a) no process involving ignition sources (including temporary storage of heat sources) is allowed outside the glovebox and (b) no flammable materials are stored outside the gloveboxes except for flammable gases, which are stored in pressure vessels. It is interesting that PF-4 hazards analyses also did not identify any process that would start a fire outside the glove box, in a laboratory room. Given zero PF-4 laboratory room fires in the 18 yr from 1981 through 1998, the median frequency of laboratory room fires at PF-4 can be estimated to be 0.04/yr, with 5th and 95th confidence values of 0.003/yr and 0.15/yr, respectively.[13] The 95th confidence value of 0.15/yr was used in this study to address the eventuality that a human error or other random events can cause ignition in the laboratory room, outside the glovebox. These values compare as follows with the data from other facilities.

Two documents published by the DOE's Office of the Deputy Assistant Secretary for Safety and Quality Assurance ("Summary of Fire Protection Programs of the US DOE Calendar Year 1991" and "Summary of Fire Protection Programs of the US DOE Calendar Year 1992") and an unpublished book by Walter Maybe ("AEC/ERDA/DOE Fire Protection History," August 1995) indicate that across the DOE Complex, there were 280 room fires between 1975 and 1990, 120 fires in 1991 and 131 fires in 1992. Based on the preceding data, there were at least 531(= 280 + 120 + 131) fires during the 18-yr inclusive period between 1975 and 1992. These data cover over 10,000-laboratory building-years of operation and result in a mean frequency of 0.05/yr. This value is lower than the frequency of 0.15/yr used in the present study.

Fire incident data pertinent to the DOE's Rocky Flats site was documented in the Stone and Webster Engineering Company Report title "SFAR Review Team Report on Rocky Flats Building 707" (Volume 1, Main Report, November 1991). This report summarizes Rocky Flats building fire events that occurred outside gloveboxes but inside modules at several plutonium-related buildings. There were 94 of these types of fires among several Rocky Flats plutonium buildings (559, 707, 771, 776/777, and 779) over an interval of 175 building-years. Per these data, the frequency of a room fire at Rocky Flats during the reporting period was about 0.5 per building per year. This value is higher than the value of 0.15/yr used in the present study to represent the frequency of a laboratory room fire in the PF-4 building.

Ignition Inside the Glovebox

Per the TA-55 UOR data previously described, a total of 10 occurrences of glovebox fires or glovebox fire precursor events was identified at TA-55 for the years 1981 through 1998 inclusive. These 10 glovebox incidents are summarized in Table 3-1. The sources for the events summarized in Table 3-1 are internal memos and the referenced database reports collected for the period 1981 through 1998. Again, the history before implementation of the Pre-ORPS database in September 1990 may be incomplete.

Table 3-2 summarizes the TA-55 glovebox fire and fire precursor statistics as derived from Table 3-1. There are 10 fires or fire precursor events for 1981 through 1998. As indicated in Table 3-2, six of these events occurred from 1991 onward, a time interval for which the recorded data are complete. Therefore, the point estimate rate of glovebox fires at TA-55 over the 8-yr period from 1991 through 1998 inclusive is 0.75 per year.

This value is conservative because some of the recorded events are precursors and did not include an actual ignition. The extent of conservatism can be demonstrated by considering an event-tree model (Fig. 3-1) that displays the pathways by which each event category can lead to a glovebox fire. For explosion/fire events, the

[13] Non-zero estimates for median, 5th and 95th confidence values were derived from a binomial probability distribution given zero observed fires in 18 yr.

Table 3-1
List of Fires and Fire Precursor Events for TA-55 Gloveboxes–1981 through 1998

Applicable UOR	Event Description	Type of Event	Remarks
SPMS-82701	Ignition of either smoke generated during incineration of mixture of plastics and damp and rinsed and dried (cheesecloth) rags or of the rags themselves resulted in glovebox over-pressurization; two windows blown off glovebox.	Explosion/fire	Accident may be applicable to other oxygen-sparged, high-temperature reduction of organic materials processes. Alternate process considered but no indication whether process changed.
SPMS-82703	Exothermic reaction during air purification of mixture of 13 sweepings over-pressurized glovebox and blew out top window. Furnace temperature lowered to 350ºF from normal 500ºF because rust-brown, sand-consistency sample (produced in 1965) was labeled “refrigerate”.	Explosion/fire	Accident occurred in spite of operator’s precautions. Procedures instituted to analyze and/or reduce questionable samples to metal and to prevent mixing of characterized and uncharacterized samples.
SPMS-85755	Mixture of polypropylene filters in nitric acid dried out and ignited during overnight hot-plate digestion process. Heat detector worked; glovebox train successfully isolated and fire starved.	Overheated equipment	Hot-plate temperature set too high.
SPMS-87755	Thermocouple wiring insulation contacted furnace element after normal working hours. Guard noticed resulting smoke and pulled manual fire alarm, which did not operate. Guard called control room operator, who confirmed no alarm was received; guard pulled another alarm that operated successfully.	Overheated equipment	No indication that control room operator independently contacted fire department.
ALO-LA-TA-55-1993-0036	Spark from plasma arc cutter ignited pile of cheesecloth rags; fire tamped out using a glove, and fire embers sprayed with liquid cleaning fluid (Fantastik).	Spontaneous ignition	
ALO-LA-TA-55-1994-0033	Alcohol-wetted, plutonium-contaminated rags in open steel storage can located in a drop box thermally decomposed to ash. Plastic bottle in contact with can melted	Spontaneous ignition	Drop box heat-sensing unit having a 140ºF set point temperature did not actuate.
ALO-LA-TA-55-1994-0037	Alcohol-wetted plutonium-contaminated rags that had been removed from an externally corroded storage can spontaneously combusted in glovebox. Manual alarm actuated, glovebox manually isolated, and fire department responded to alarm.	Spontaneous ignition	During post-fire inspection, two additional similar cans discovered to have corroded exteriors and placed in inerted gloveboxes. EPA incineration stoppage has forced situation where combustibles are stored with heat-producing radionuclide.
ALO-LA-TA-55-1995-0002	Oxidized metal being scraped form metalographic sample fell onto nearby terry cloth, which ignited. Employee placed towel in transfer box and inerted box.	Spontaneous ignition	Glovebox heat-sensing unit having a 190ºF set-point temperature did not actuate.
ALO-LA-TA-55-1997-0008	During crushing and pulverizing operation employee noticed excessive plutonium residue smoldering in a catch pan. Employee covered can with steel lid (provided for this purpose) and inerted glovebox.	Spontaneous ignition	Smoldering reaction is anticipated to occur during crushing and pulverizing operations.
ALO-LA-TA-55-1998-0038	Employee observed smoke coming from a trolley system electric motor. Employee de-energized motor and actuated manual fire alarm. Fire department successfully responded to alarm.	Overheated equipment	Not a combustion event.

Table 3-2
Summary of Fires and Fire Precursor Events for TA-55 Gloveboxes

Event Category	Number of Events
TA-55 UOR Data From 1981 Through 1998, Inclusive (18 yr period)	
Explosion/Fire	2
Spontaneous Ignition	5
Overheated Equipment	3
Total 1981–1998	10
Frequency (per year)	**5.6×10^{-1} (mean, point estimate)**
TA-55 UOR Data From 1991 Through 1998, Inclusive (10 yr period)	
Explosion/Fire	0
Spontaneous Ignition	5
Overheated Equipment	1
Total 1991–1998	6
Frequency (per year)	**7.5×10^{-1} (mean, point estimate)**

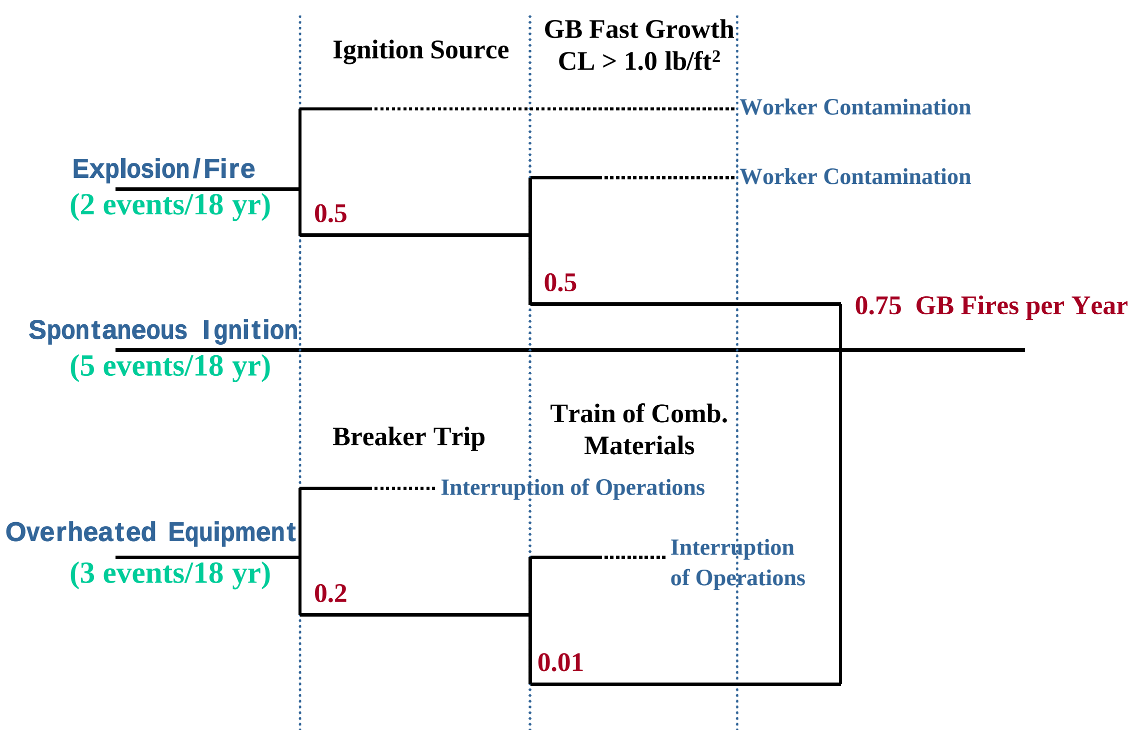


Fig. 3-1. Pathways that may lead to a glovebox fire.

occurrence of a fire requires that a post-explosion ignition source be present. Without an ignition source, the event will simply lead to worker contamination. Given an ignition source, the fire will be self-limiting unless the quantity of combustible materials inside the glovebox is greater than 3 lb. Given a post-explosion ignition source and sufficiently high combustible loading, the explosion event will lead to a glovebox fire as shown in Fig 3-1. Using the split fraction data, a glovebox fire resulting from an explosion would occur only 25% of the time. However, to be conservative, an explosion event was assumed to result in a glovebox fire 100% of the time. Similarly, events involving overheated equipment often do not lead to fires. As indicated in Fig. 3-1, there is a significant possibility that protective circuit breakers will interrupt electrical current to overheated equipment before a fire can occur. Even if flames erupt, there is only a small probability that there will be a sufficient quantity of combustible materials in the immediate vicinity of the overheated equipment to sustain the fire. Again, to be conservative, events involving overheated equipment were assumed to result in a glovebox fire 100% of the time.

Total Frequency of Ignition in a Laboratory Room

Based on the preceding considerations, the frequency of glovebox fires at TA-55 was assumed conservatively to be 0.75/yr. This frequency estimate was added to that obtained for ignition outside the glovebox (0.15/yr.) to arrive at the frequency of a randomly caused PF-4 laboratory room fire of 1/yr. Given that there are 115 rooms in PF-4, the frequency of a fire occurring in any particular room was estimated conservatively to be 9×10^{-3}/yr.

In summary, various methods have been used to estimate the frequency of fires at PF-4. The frequency estimates are summarized in Table 3-3.

3.2. Formulation of Success Criteria for Fire Containment

Deterministic analyses (described in Appendices A and B) were used to derive a set of success criteria related to containment of fire during various stages of its progression. This section summarizes the success criteria.

Criteria for Fire Contained in the Local Area Where It Was Started: For a fire to be contained within the local area, **either** (a) the operator should contain and extinguish fire within the first few minutes **or** (b) local fuel loading should not exceed 1 lb/ft^2. No qualified fire barriers exist within a room to prevent fire spread beyond the local point of ignition. This criterion takes into consideration that (a) because of possible release of radioactivity into the laboratory room, TA-55 worker response will be limited to few minutes after ignition and (b) a fuel loading of 1 lb/ft^2 will not lead to flashover [see Item (A) in Fig. 3-2].

Criteria for Fire Contained in the Laboratory Room in Which It Started: Two-hour NFPA-qualified fire barriers separate each room from the adjoining rooms, basement, and attic. In addition, each laboratory room is equipped with 212^{o}F wet-pipe fire sprinklers. For fire to be contained in the laboratory room of origin, **either** (a) the fire sprinkler system must actuate and provide adequate water flow **or** (b) effective combustible loading in the room must not exceed 8 lb/ft^2. Fire containment by Los Alamos fire fighters is not credited in this study. This criterion takes into consideration propagation of fire to the adjoining rooms as a result of (a) flashover resulting from hot fire gases leaking through open wall penetrations and (b) thermal failure of the fire wall [see Item (B) in Fig. 3-2].

Criteria for Fire Contained in the Area: The only possible mechanism for fire spread throughout the area (or a major portion of the area) is flashover, a mechanism by which hot combustion gasses leaking from one room to the other ignite flammable materials. For this condition **not** to occur (a) the effective combustible loading in the room adjacent[14] to the room where the fire started must not exceed 8 lb/ft^2 or (b) the Zone 1 ventilation system fails (thus limiting the spread of hot gases). Fire containment by Los Alamos fire fighters or sprinkler system recovery from the failed state is not credited in this study. This criterion takes into account the enhanced propagation of fire from one area to the other by flashover when the HVAC system is operational [see Item (C) in Fig. 3-2].

[14] Any room next to the room with the initial fire and in the same area is an “adjacent” room. A room across the corridor or in another area across from the room with the fire is not considered an adjacent room.

Table 3-3
Summary of Frequency Estimates for Room and Glovebox Fires and Precursor Events

Frequency of Fire (per year)	Method Used to Estimate Frequency	Notes
Ignitions outside glovebox (per year)		
Used in this Study PF-4 Bldg.: 0.15 (95th percentile) Per Room: $9x10^{-3}$	TA-55 UOR data, binomial distribution for 0 fires out of 18 yr with 95% confidence.	Represents the frequency of a laboratory room fire out of the total population of laboratory rooms in TA-55 For PF-4, there are 115 rooms; thus, the frequency of a fire per room per year at PF-4 would be 0.15/115 = **$9x10^{-3}$.**
All DOE Laboratory Rooms Per Bldg.: $3x10^{-3}$ (mean)	Statistics of fires averaged over numerous DOE facilities	Represents frequency of a laboratory room fire out of the total population of laboratory rooms in a representative DOE building
Rocky Flats Experience Per Bldg.: 0.5 (mean)	Rocky Flats operational data	Represents frequency of a laboratory room fire estimated from Rocky Flats experience. Major differences exist between Rocky Flats and PF-4 regarding construction, operation and administrative controls.
Ignitions inside glovebox (per year)		
Used in this Study PF-4 Bldg.: 0.75 (Mean) Per GB $1.9x10^{-3}$ (mean)	TA-55 UOR data	Annual rate of fires or precursor events summed over all 400+ gloveboxes at PF-4 is **$7.5x10^{-1}$/yr** (mean)
Rock Flats Experience: PF-4 Bldg.: 10 (Mean) Per GB: $2.5x10^{-2}$	Rocky Flats operational data. This number represents a high-end estimate because (1) the majority of the glovebox fires occurred before installation of glovebox inerting systems at Rocky Flats and (2) Rocky Flats typically processed larger quantities of materials than TA-55, thereby increasing the chances that a glovebox fire would occur there	Per individual glovebox. Rocky Fats experience of $2.5x10^{-2}$ per glovebox per year was multiplied by 400 to obtain 10 glovebox ignitions per year. These data are not applicable to PF-4 because PF-4 gloveboxes are inerted and they do not process nearly as much material as the gloveboxes at Rocky Flats.

Criteria for Fire Contained in the Wing: For a fire in one wing not to propagate to the other wing as a result of flashover, the following must be satisfied [see Item (D) in Fig. 3-2].

- Both of the two sets of doors in the H-wall on the upper level must remain closed, **AND**
- Both of the two sets of doors in the H-wall in basement must remain closed, **AND**
- One of the two fire dampers in the trolley crossover line must remain closed.

In summary, a small fire in a PF-4 room is postulated to grow into a larger room fire if the manual fire suppression fails to act and the local combustible loads exceed 1 lb/ft^2. A large room fire was assumed to propagate into an adjacent room via flashover if the fire suppression fails and the combustible loading exceeds 8 lb/ft^2 in the burning room. If an adjacent room also has a combustible loading that exceeds 8 lb/ft^2, the fire then can spread to the associated PF-4 Area (i.e., 100, 200, 300, or 400). If the ventilation system remains on, an area fire can propagate to the associated wing (i.e., North or South). The combustible loading in various PF-4 regions is insufficient to allow fire propagation through the interior fire barrier (H-wall) separating the two wings. However, if a mechanical pathway through the H-wall exists, a wing fire can spread into the remaining wing, resulting in a building-wide fire. An H-wall mechanical pathway is created if a trolley line crossover is open, an upper or lower level door is open, or an H-wall penetration is open for test/maintenance activities. It again is emphasized that fire

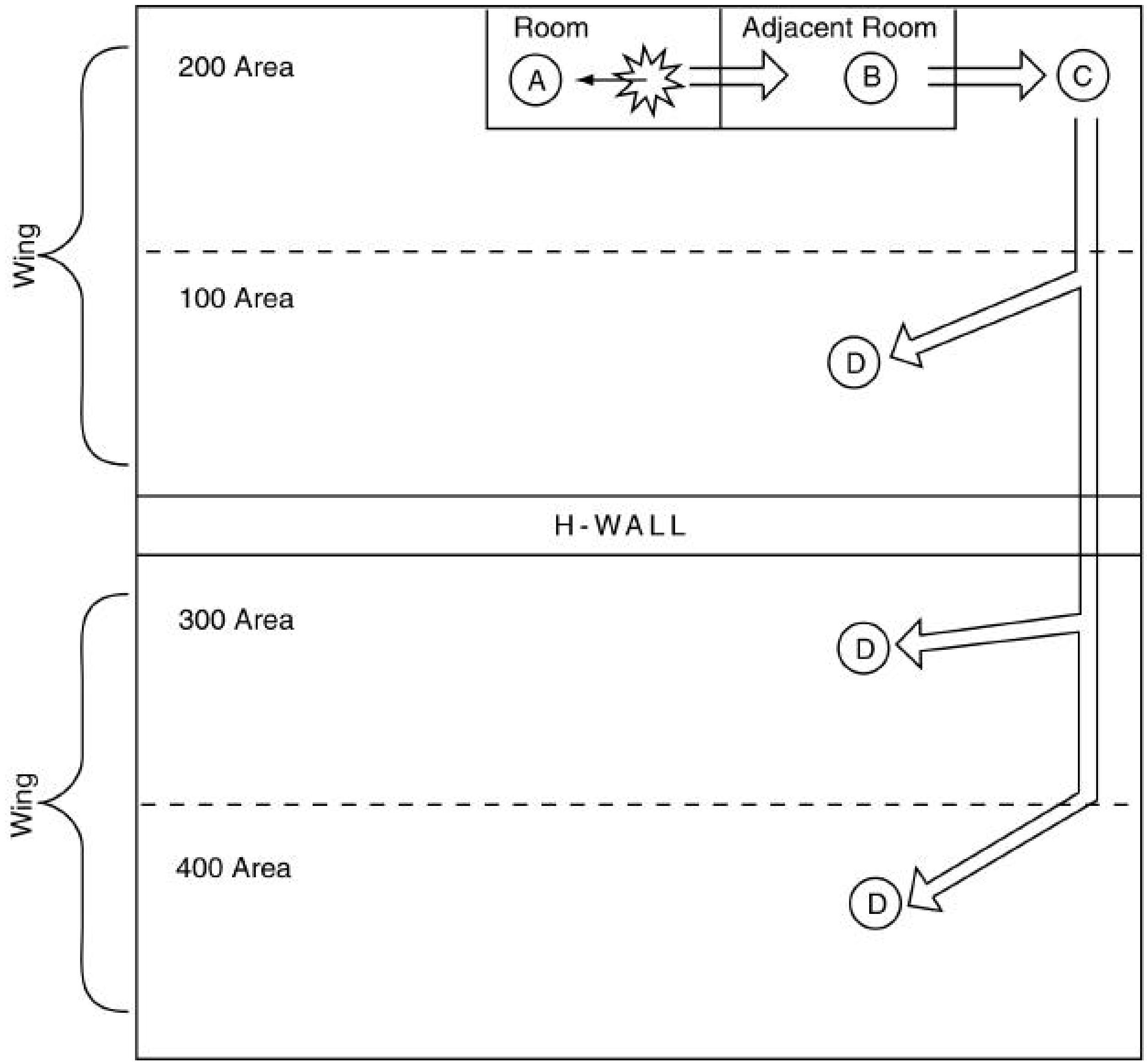


Fig. 3-2. Overview of fire progression.

propagation also requires failure of the automatic and manual fire suppression. Also, this study does not credit either the Los Alamos fire department response or the TA-55 staff response to recover a failed fire suppression system.

Alternatively, a building-wide fire can be avoided if <u>any</u> of the following conditions exist.

- Manual fire suppression actions in less than 2 min *or*
- Operation of the automatic fire suppression system *or*
- Quantity of combustible material in the local area where fire started does not exceed 1 lb/ft^2 *or*
- Quantity of combustible material in the room where fire started does not exceed 8 lb/ft^2 *or*
- Quantity of combustible material in any room adjacent to the ignition area does not exceed 8 lb/ft^2 *or*
- Ventilation system is off (either turned off or fails because of high gas temperature) *or*
- All interior fire pathways between wings (H-walls) are closed

3.3. Quantification of Fire Spread Sequences

As discussed above, a PF-4 room fire can propagate into a PF-4 area *if and only if* each of two adjacent rooms has a combustible loading in excess of 8 lb/ft^2. In addition, the fire would have had to originate in one of these rooms. Based on facility walkdowns and reviews of facility records and documentation, only one set of PF-4 rooms was identified where these criteria can be met, namely, Rooms 207 and 208. Room 207 usually has a combustible loading in excess of 8 lb/ft^2, and Room 208 normally contains about 6 lb/ft^2 of combustible material, although historical experience indicates that the amount of combustible material exceeds 8 lb/ ft^2 approximately 0.26% of the time. No other room at PF-4 has combustible loads (transient plus fixed) larger than 2.5 lb/ft^2. Therefore, for a fire to propagate beyond the room of its origin, (a) it has to originate in Room 207, spread to Room 208, and, given sufficient combustible loading in Room 208, subsequently spread to the PF-4 200 Area, **or** (b) the fire could originate in Room 208 during a period where combustible loading exceeds 8 lb/ft^2, spread to Room 207, and subsequently spread throughout the remainder of the PF-4 200 Area.

3.3.1. Event-Tree Model. Figure 3-3 shows the event tree used in the analysis. This event tree portrays the possibilities for the progression of a room fire. The event tree is structured so that the progression of the accident is represented in a time-ordered manner from left to right. In this model, successful mitigation of the room fire occurs whenever the fire is contained before it becomes the building-wide fire.

There are five headings on the event tree. Starting from the left, the first heading represents the room fire-initiating event: fire started in Room 207 or 208. The second heading is used to indicate whether the source of ignition is extinguished. The third heading represents the status of the fire with regard to containment in the room of origin. Likewise, the fourth and fifth headings represent the status of the fire with regard to area and wing containment, respectively.

The event tree has five sequences; four (OF-1 through OF-4) represent success (no building-wide fire), whereas Sequence OF-5 represents failure (a building-wide fire). Each of these sequences is described in more detail below.

Sequence OF-1 represents the situation where either (a) the ignition source in the room is extinguished by workers in the vicinity or (b) local combustibles loads are low (do not exceed 1lb/ft^2).

In Sequence OF-2, workers are unavailable to extinguish the fire. However, the fire is contained in the room of origin because either (a) the fire water suppression system successfully operates or (b) the combustible loading in the room does not exceed 8 lb/ft^2. (As previously discussed, the room combustible loading must exceed 8 lb/ft^2 before a room fire can fail the room firewalls.)

In Sequence OF-3, an initial room fire propagates into adjacent room(s). The fire is able to propagate beyond the room of fire origin because fire suppression is unavailable and the room has a combustible loading that exceeds 8 lb/ft^2. However, fire propagation beyond the room of origin and the adjacent room(s) into the entire wing is avoided because (a) the combustible loading in room(s) adjacent to the room of fire origin does not exceed 8 lb/ft^2 or (b) the ventilation system is turned off. The building confinement system is intact for this sequence; thus, item (b) has little contribution.

In Sequence OF-4, an initial room fire propagates into an entire wing. For this situation to occur, combustible loading in both the room of fire origin and an adjacent room must exceed 8 lb/ft^2 and the building ventilation system must be on. (As in Sequence OF-3, the fire suppression system in the room of fire origin has failed.) Fire propagation into the entire building is prevented because all interior fire pathways between wings (H-walls) are closed.

Sequence OF-5 is similar to Sequence OF-4, except that Sequence OF-5 includes an open H-wall pathway between wings. An H-wall pathway can occur from an open trolley line crossover, an open upper or lower door, or an H-wall penetration that happens to be open for test/maintenance activities. Given an open H-wall pathway, a building-wide fire is postulated to occur.

3.3.2. Sequence Quantification. Per the discussion in Sec. 4.1.2, the frequency of fires per room at PF-4 was assumed to be $9x10^{-3}$/yr. This value was used to represent the frequency of fire in either Room 207 or 208 to be

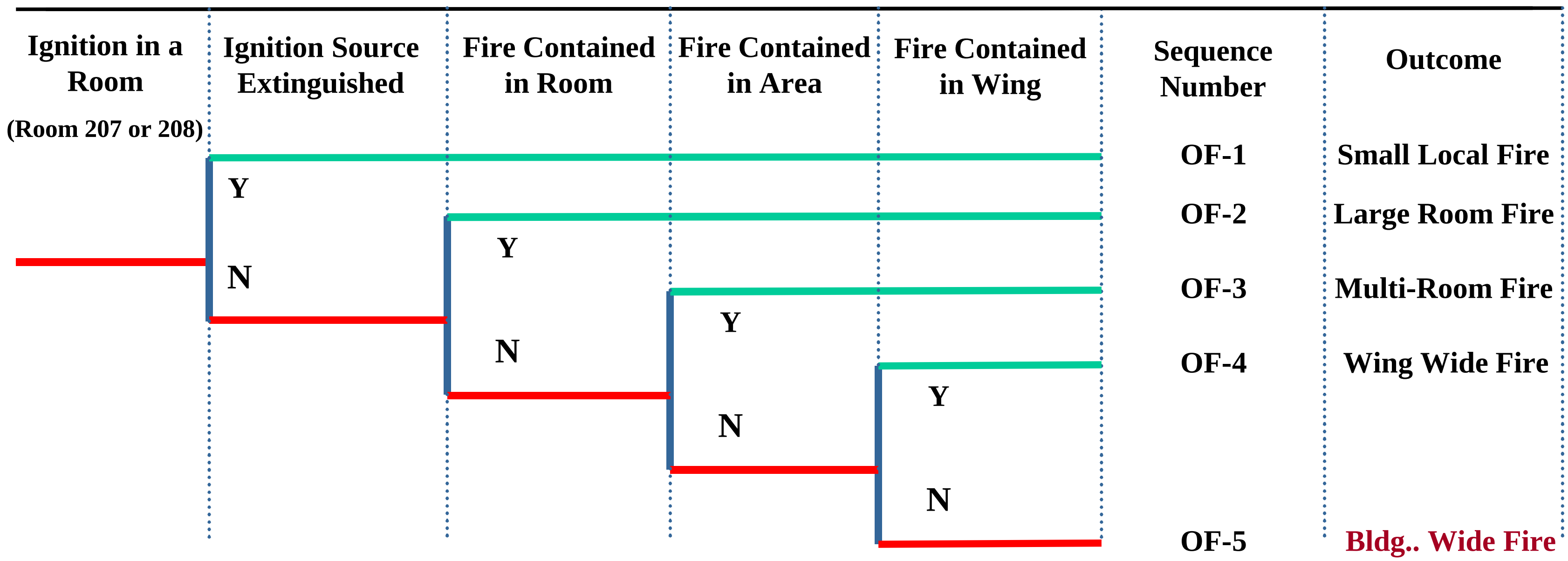


Fig. 3-3. Event tree used in operational fire analysis.

$2x10^{-2}$/yr. Use of this number for Room 208 is conservative because it is not very common that Room 208 has a fuel loading in excess of 8 lb/ft^2.

Fault-tree models were developed to evaluate split fraction probabilities for the other event tree headings.

- Ignition Source Extinguished (indicates whether a fire has been extinguished in source region)
- Fire Contained in Room (status of the fire with regard to room containment)
- Fire Contained in Area (status of the fire with regard to area containment)
- Fire Contained in Wing (status of the fire with regard to wing containment)

The fault-tree models for the above event-tree headings are summarized below. A complete set of fault trees and quantification data is provided in Darby (1999).

The fault tree for the event tree heading "Ignition Source Extinguished" models the possibility that a fire in Room 207 or 208 cannot be extinguished in the room of origin (downward portion of the split fraction). As explained previously, there must be in excess of 1 lb/ft^2 of combustibles in a room for an initiator not to self-extinguish. Given that the fire is assumed to originate in either Room 207 or Room 208, which have combustible loads in excess of 1 lb/ft^2, the postulated fire initiator will not self-extinguish. The probability that on-site workers manually extinguish the fire was determined by the fraction of time that workers would not be present, which is approximately 76% of the time. (Workers were assumed to be present 40 h per week.)

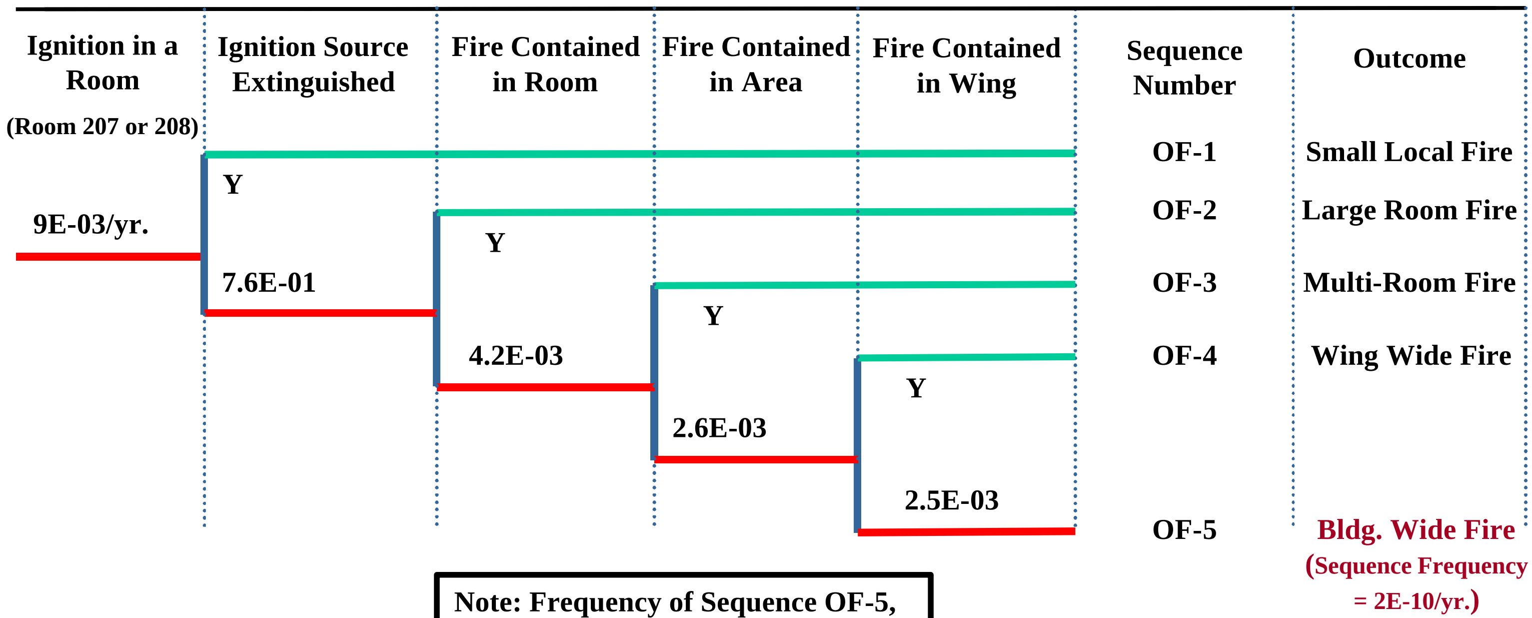
The fault tree for event-tree heading "Fire Contained in Room" represents the possibility that the fire is not contained in its room of origin but will instead propagate to an adjacent room (downward portion of the split fraction). This fault-tree logic requires that the combustible loading in the fire origination room exceed 8 lb/ft^2 along with failure of the FWSS. These two elements of the fault tree are combined together in **AND** logic. The fault-tree structure for the FWSS is developed further into the sprinkler and water supply subsystems. The required support systems, for example, electrical power, also are modeled. The sprinkler and water supply and their support systems are developed to the component level. It was modeled that one of four fire water supply pumps would provide sufficient flow to the sprinklers. Quantification of the fire water supply fault tree was based on TA-55 specific data and operating experience to the extent possible.

The event-tree heading "Fire Contained in Area" represents the possibility that a fire that has expanded into an adjacent room will propagate into an area-wide fire (downward portion of the split fraction). The corresponding fault-tree logic requires that the combustible loading in the room adjacent to the fire origination room exceeds 8 lb/ft^2 and that the ventilation system operates. These two elements of the fault tree are combined together in **AND** logic. As previously discussed, Room 207 usually has a combustible loading in excess of 8 lb/ft^2, whereas Room 208 has this level of combustible loading about 0.26% of the time. For this analysis, it was assumed conservatively that the ventilation system would be on during the fire. Therefore, the corresponding event representing ventilation system operation was assigned a probability of 1.

The fault tree for event-tree heading "Fire Contained in Wing" represents the possibility that the wing fire will propagate to the remaining wing, resulting in a building-wide fire (downward portion of the split fraction). Propagation of a wing fire into a building-wide fire will occur if an interior fire wall barrier (H-wall) is open. The fault tree models the four possible methods by which an H-wall pathway can occur: an open trolley line crossover, an open upper level door, an open lower level door, or an H-wall penetration that is open for test/maintenance activities. Quantification of the fault-tree bottom events was based on TA-55 specific data and operating experience where possible.

3.4. Results and Discussions

Figure 3-4 shows the split fractions and sequence frequencies for a fire initiated in either Room 207 or Room 208. Per the analysis, a building-wide fire has a point-value frequency estimate of $2x10^{-10}$/yr. Given that a fire could occur in either Room 207 or Room 208, the overall point-value estimate for the frequency of a building-wide fire is $4x10^{-10}$/yr.



Note: Frequency of Sequence OF-5, 2E-10/yr., is a result of a fire in either Room 207 or Room 208; the total frequency of a building-wide fire is therefore <u>4E-10/yr.</u>

Fig. 3-4. Event tree results for operational fire in PF-4.
Note for example: 9E-03 = 9×10^{-3}

The very low frequency of a building-wide fire is a result of a combination of the following low-frequency/probability events.

1. The frequency for a random fire in one of only two rooms that has sufficient combustible loading to promote fire propagation (either Room 207 or 208): $9x10^{-3}$/yr.
2. The conditional probability for failure of the fire water suppression system: $4.2x10^{-3}$.
3. The conditional probability that combustible loading in a room adjacent to the room of fire origin is sufficient to allow fire propagation: $2.6x10^{-3}$.
4. The conditional probability that penetrations in the H-wall are open, thus allowing fire to spread to the other wing: $2.5x10^{-3}$.

There is one relatively high probability event, namely, ignition source not extinguished by local worker response, which has a conditional probability of 0.78. The product of these probabilistic data for these independent events is essentially the frequency of a building-wide fire because there is little sharing of structures, systems, and components (SSCs) among the constituent events in the sequence.

Two dominant cut sets[15] collectively represent about 46% of the total building-wide fire frequency. The most dominant sequence cut set, which represents about 29% of the building-wide fire frequency, includes two important failure events: (a) failure of the sprinkler alarm check valve to open on demand and (b) failure of the room heat detector to close cross-over trolley dampers. The second most dominant cut set, representing about 17% of the building-wide fire frequency, includes the following important failure events: (a) failure of the sprinkler alarm check valve to open on demand and (b) an H-wall penetration that is open for test/maintenance activities.

3.5. Limitations and Conservatism

A number of conservative assumptions were made in this analysis. Examples of some of these conservative assumptions are summarized below.

- Even though there have been no instances of laboratory room or basement fires at TA-55, the analysis assumed that a room fire would occur with the frequency of glovebox fires. Furthermore, the frequency of glovebox fires was estimated conservatively by including several events that were only potential fire precursor events and not actual fires.
- Deterministic calculations indicate that for a flashover fire to occur, combustible loadings in two adjacent rooms must each exceed 8 lb/ft^2 and the combined floor area of these rooms must exceed 4500 ft^2. There are no pairs of adjacent rooms in PF-4 where this situation occurs. The analysis conservatively assumed that flashover could occur simply if the 8-lb/ft^2 combustible room loading was met without consideration of the total floor area.
- It was assumed that laboratory room doors would remain open during a fire scenario. Closed room doors would represent a 1.5-h fire barrier.
- No credit was taken for the response and mitigating actions of dedicated, off-site fire department personnel.
- Propagation of an area-wide fire to an entire wing requires that the ventilation system remain on. The analysis conservatively assumed that the ventilation system would be on during the fire sequences.

4.0. BUILDING-WIDE FIRE RESULTING FROM SEISMIC EVENT

4.1. Overall Approach for Seismic Analysis

The analysis method used in the seismic analysis is largely based on an approach described by Kennedy et. al. (R. P. Kennedy et. al. *Probabilistic Seismic Safety Study of an Existing Nuclear Power Plant,* Nuclear Engineering and Design Vol. 59, pp. 315-338, March 1980). The three major Analysis Elements used in the TA-55 approach are:

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[15] A "cut-set" is a combination of the initiating event (fire) and a specific set of subsequent failure events that result in a building-wide fire.

1. Estimate the ground motion (peak ground acceleration) as a function of the annual frequency of occurrence,
2. Estimate the conditional probability of failure for structures, equipment, etc. as a function of ground acceleration (fragility), and
3. Combine the estimates from elements (1) and (2) into system and event tree models to estimate the frequency of seismic-induced fires that release bulk Pu.

Section 4.1.1 summarizes Analysis Element (1), the quantification of seismic initiating event frequencies at TA-55. Section 4.1.2 describes Analysis Element (2), which involves the development of system and component fragility curves. Analysis Element (3), the quantification of fire-related Pu releases, is summarized in Sec. 4.1.3. Further details on the analysis approach are provided in Darby (1999).

4.1.1. Quantification of Initiating-Event Frequency. The frequency of a seismic event cannot be represented by a single value because the frequency of a seismic event is a strong function of the resulting ground motion. The seismic hazard at a given site is represented most easily by a plot of the annual frequency of exceedance vs peak ground acceleration (PGA). Figure 4-1 displays the annual frequency of exceedance vs PGA for the TA-55 site as developed by Woodward-Clyde Federal Services. This figure includes separate curves representing mean, median, 16^{th}-84^{th} percentiles, and 5^{th}-95^{th} percentiles. The mean value curve in Fig. 4-1 was used to generate frequency estimates for seismic activity at TA-55. The analysis sampled the entire seismic hazard curve.

The annual frequency of occurrence for a seismic event within a specific PGA interval can be obtained from the differential of the frequency of exceedance curve with respect to the PGA. Specifically, let $H(x)|_x = X$ be the function in Fig. 4-1 representing the frequency that a seismic event exceeds a specific PGA of value X. Then, – $(dH/dx)|_{x=X} * dx$ is the frequency for an initiating event with a PGA that is in the interval (X, X + dx); the minus sign is necessary because H is an exceedance function.

4.1.2. System/Component Fragility Curves. Fragility curves were developed to account for the ability of various TA-55 structures, systems, and components (SSCs) to withstand a seismic event. The fragility of an SSC is defined as the conditional probability of the SSC's failure given a specific value of the PGA.

An approach described by R. P. Kennedy and as implemented by L. Goen of Los Alamos was used to derive best-estimate fragility curves for the various SSCs modeled in the analysis. (References: R. P. Kennedy et.al. Probabilistic Seismic Safety Study of an Existing Nuclear Power Plant, Nuclear Engineering and Design 59 (1980), pp. 315-338, March 1980; LANL Memorandum to P. Pan from Larry Goen, March 3, 1995.) Using this approach, the best-estimate fragility curve for a component is represented in Eq. (1) as $P_{fail}(x)$, where x is a given value for the PGA.

$$P_{fail}(x) = \Phi\left[\frac{\ln\left(\dfrac{x_{cg}}{\frac{HCLPF_{84\%}}{1.2}e^{2.326\,b}}\right)}{b}\right] \qquad (1)$$

In the above equation, Φ(z) is the cumulative normal distribution function for the standard variable z (z has a mean of 0 and a standard deviation of 1). For this application, z is the argument of Φ as given in Eq. (1). The variable x_{cg} is the PGA at the center of gravity of the SSC. $HCLPF_{84\%}$ is the HCLPF value at a reference PGA where the response spectrum (actual frequency/acceleration spectrum seen by the SSC) is not exceeded with 84% confidence.[16] The quantity β is a composite logarithmic standard deviation representing both random (stochastic) and state-of-knowledge (epistemic) uncertainty. Here $\beta = (\beta_R^2 + \beta_U^2)^{0.5}$, where β_R and β_U represent random and state-of-knowledge uncertainty, respectively.

[16] The HCLPF capacity represents a 1% to 2% probability of failure for the component.

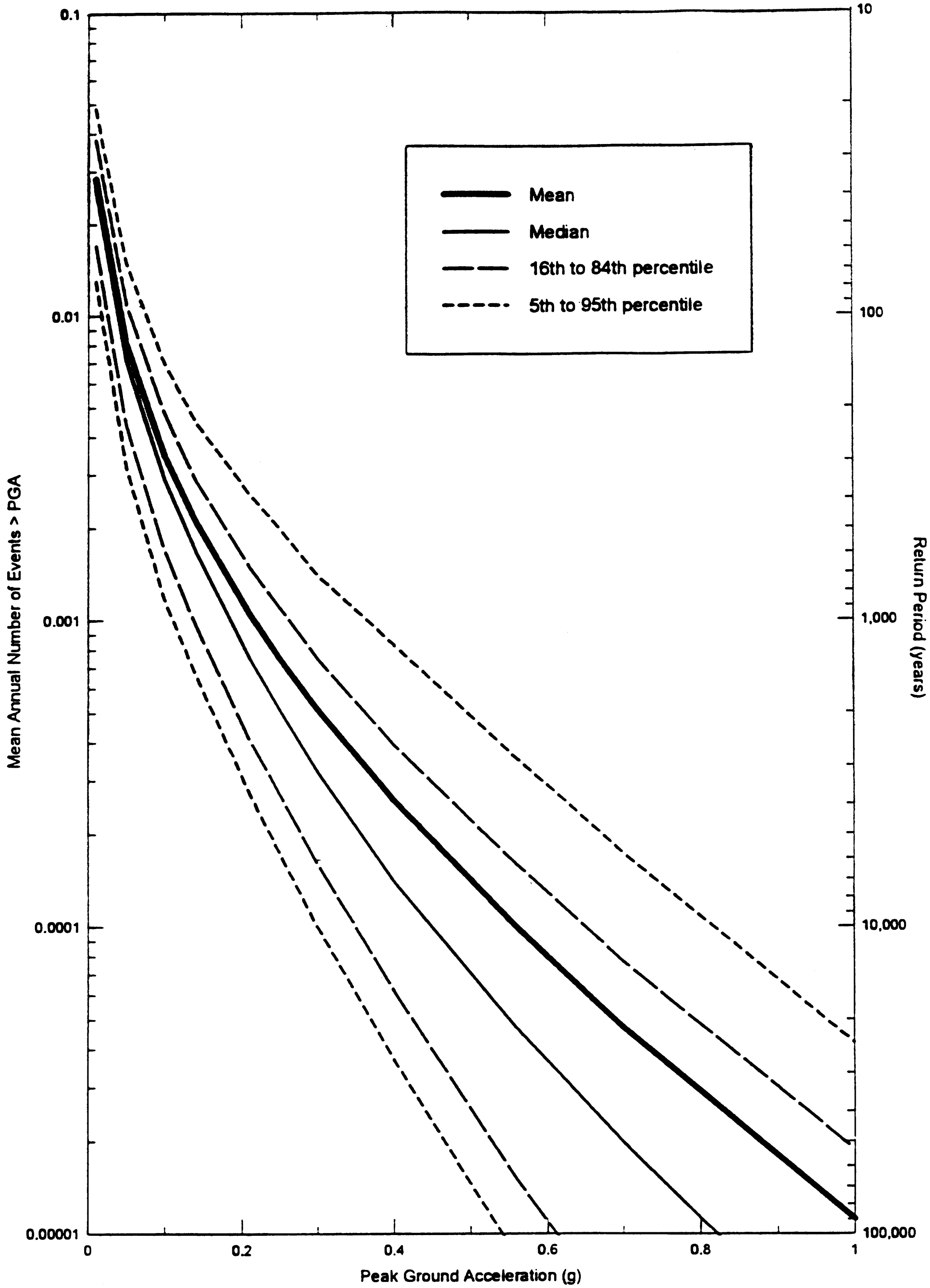


Fig. 4-1. Frequency of exceedance seismic data for TA-55.

The $HCLPF_{84\%}$ values for SSCs at PF-4 were estimated based on walkdowns of the facility and design information for the SSCs in the facility. The $HCLPF_{84\%}$ values used in the analysis for individual SSCs are summarized in Table 4-1. A value of 0.4 was used for the standard deviation parameter β.

Additional details regarding the fragility calculations are provided in Darby (1999), including the methods used to treat dependence among gloveboxes.

4.1.3. Quantification of Accident Frequencies. The seismic event is the initiating event for the accident and, as such, is quantified as a frequency. Per Sec. 4.1.1, the frequency for an initiating event with a magnitude in the interval (X, X + dx) is represented by $-(dH/dx)|_{x=X} * dx$, where $H(x)|_x = X$ is the function that represents the frequency that a seismic initiating event exceeds a specific PGA value of X. Let $P(A \mid x)|_{x=X}$ be defined as the probability that a particular component A fails given x is a specific value X; it is assumed that $P(A \mid x)|_{x=X}$ is uniquely defined given X. If f(x) is defined to be $\equiv -(dH/dx)$, the overall frequency for the initiating event followed by failure of component A is given in Eq. (2):

$$\int f(x)\, P(A \mid x)\, dx \qquad (2)$$

This approach can be extended to consider a cut set of events with each event representing the failure of an SSC because of an external event. Let $P_{jm}(x)$ be the function that represents the probability that an SSC designated as m in cut set j fails at magnitude x. The frequency of the j^{th} cut set is given in Eq. (3).

$$\int -\left(\frac{dH}{dx}\right)\prod_m P_{jm}(x)\, dx \qquad (3)$$

Using the rare event approximation, the accident frequency is calculated from Eq. (4).

$$f \;=\; \sum_j \int -\left(\frac{dH}{dx}\right)\prod_m P_{jm}(x)\, dx \;=\; \int \sum_j -\left(\frac{dH}{dx}\right)\prod_m P_{jm}(x)\, dx \qquad (4)$$

The integrand weights each probability by the likelihood of the initiating event at a specific x, and the integration is over all x. In Eq. (4), j denotes a cut set, m denotes a basic event in a cut set, and n denotes a mesh point in the discrete set of bins for the magnitude x.

Table 4-1
Summary of $HCLPF_{84\%}$ Values Used in the Analysis

Structure, System, Component (SSC)	$HCLPF_{84\%}$ (g)
Fire water piping (in fire suppression system)	0.19
H-wall (crossover trolley dampers)	0.78
Interior fire walls	0.59
Gloveboxes that are ignition sources	
Room 207 (three ignition-source gloveboxes)	0.13 (one glovebox), 0.24 (one glovebox), 0.5 (one glovebox)
Room 208 (five ignition-source gloveboxes)	0.08 (all five gloveboxes)
Room 209 (four ignition-source gloveboxes)	0.08 (two gloveboxes), 0.09 (one glovebox), 0.11 (one glovebox)
Other Rooms (about 10% of the gloveboxes are ignition sources)	Wide range; many at about 0.1
Building	0.77

The minimal cut set upper bound is a better approximation than the rare-event approximation for independent events. Using the minimal cut set upper bound, the accident frequency is calculated as shown in Eq. (5):

$$f \quad = \quad \int -\left(\frac{dH}{dx}\right)\left[1 \quad - \quad \prod_{j}(1 \quad - \quad \prod_{m} P_{jm}(x)\,)\right] dx \tag{5}$$

Equations (4) and (5) do not consider uncertainty in the H and P functions; that is, these equations account for randomness but not uncertainty. Best-estimate functions for H(x) and for P(x) should be used in Eqs. (4) and (5) to provide the best-estimate point value for the accident frequency. (To consider uncertainty, families of curves for H and P can be generated, each with a specific confidence.)

Equations (4) and (5) imply that every event is dependent on x; that is, every failure probability is a function of the magnitude of the external initiating event. Random failures not dependent on x can also occur; this is a degenerate case in which certain of the $P_{jm}(x)$ are constants independent of x.

An event tree was constructed to delineate the various fire-related scenarios at TA-55, while fault trees were used to model random failures. Darby (1999) provides further details regarding the quantification of frequencies for the fire-related scenarios.

4.2. Success Criteria for Fire Containment

As discussed in Sec. 3.2.1, deterministic models were used in the operational (random) fire analysis to develop success criteria for avoiding a building-wide fire. With a few exceptions and additions, the same set of success criteria was used in the seismic analysis. These exceptions and additions are summarized in Sec. 4.2.1.

4.2.1. Success Criteria Elements Specific to Seismic Analysis. Success criteria specific to the seismic analysis are described below.

Fire Suppression. For the seismic analysis, only the automatic fire suppression system was considered as a potential means of fire suppression. Unlike the case for operational (random) fires, no credit was taken for manual fire suppression. A major seismic event would lead to evacuation of personnel from the facility, and manual fire suppression would not be feasible. Like the case for operational (random) fires, no credit was taken for a dedicated, off-site fire response force. Given a major seismic event, an off-site fire response force might not be able to travel to TA-55 because of the potential for seismic-induced damage to roadways and structures housing fire equipment. Communication also might be disrupted.

Very Many Simultaneous Fires. Although a situation involving many simultaneous fires was shown to have a negligible frequency for operational (random) fires, this situation cannot be readily screened out for a seismic initiating event. If simultaneous fires occur in a very large number of rooms, the plutonium from each room can be released if the combustible loading in each room exceeds 1 lb/ft^2. A total of 66 out of 115 rooms (57%) have a loading greater than 1 lb/ft^2. Because so many rooms have loadings in excess of 1 lb/ft^2, simultaneous fires in all these rooms are equivalent in consequence to a building-wide fire. Because these many localized fires occur on both sides of the H-wall, there is no requirement for the H-wall to fail for this case.

Ignition-Source Gloveboxes. Certain gloveboxes were identified that contain an ignition source. Given failure of this type of glovebox, it was assumed that a fire would occur with a probability of 1. Each of the ignition-source gloveboxes in Rooms 207, 208, and 209 was identified specifically. There are three ignition-source gloveboxes in Room 207, five ignition-source gloveboxes in Room 208, and four ignition-source gloveboxes in Room 209. A sampling of other PF-4 rooms taken during a walkdown identified 4 out of 40 gloveboxes, or 10%, that had potential ignition sources. Based on this walkdown, it was assumed that, on average, 10% of all gloveboxes in PF-4 would contain an ignition source.

Catastrophic Building Collapse. Given a catastrophic building collapse, it was assumed that many fires would erupt with a widespread release of plutonium. The fire suppression system would have been disabled as a result of the building collapse.

Ventilation System Status. Unlike the operational (random) fire analysis, the seismic analysis assumed that the ventilation system would not have to be operating to promote the spread of fire.

4.2.2. Summary of Success Criteria for Seismic Analysis.

A summary set of success criteria was developed based on the information presented in the preceding section. These success criteria are used to prevent either (a) a plutonium release resulting from a building-wide fire or (b) plutonium releases from many localized fires.

A plutonium release resulting from a building-wide fire will be prevented if <u>any</u> of the following conditions exist:

1. Operation of the automatic fire suppression system.
2. Favorable combustible loading in fire origin areas (all three of the loading criteria below must be satisfied):
   a) Given a single ignition source, combustible loading in the ignition source room does not exceed 8 lb/ft^2, or combustible loading in each room adjacent to the ignition source room does not exceed 8 lb/ft^2.
   b) Given a single ignition source in an adjoining set of rooms in the same wing where separation walls have failed, the combined combustible loading in these rooms does not exceed 36,000 lb.
   c) Given multiple ignition sources in an adjoining set of rooms in the same wing where separation walls are intact, the combined combustible loading in these rooms does not exceed 36,000 lbs.
3. All interior fire pathways between wings (H-walls) are closed.

A group of plutonium releases from many localized fires will be prevented if <u>any</u> of the following conditions exist:

1. Ignition-source gloveboxes are not present in the entire population of 41 rooms that contain low-fragility gloveboxes.
2. The seismic event has insufficient strength to fail the low-fragility gloveboxes in each of the above 41 rooms.
3. Favorable combustible loading exists in one or more of the above 41 rooms (i.e., the loading does not exceed 1 lb/ft^2).
4. The building structure and filtering system remain intact.

4.3. Quantification of Fire Spread Sequences

The potential for fire spread within the PF-4 building was evaluated probabilistically by developing and analyzing an event/fault-tree logic model. This model is based on the success criteria described in Sec. 4.2. Section 4.3.1 below describes the event tree used in this analysis, and Sec. 4.3.2 describes the associated fault trees.

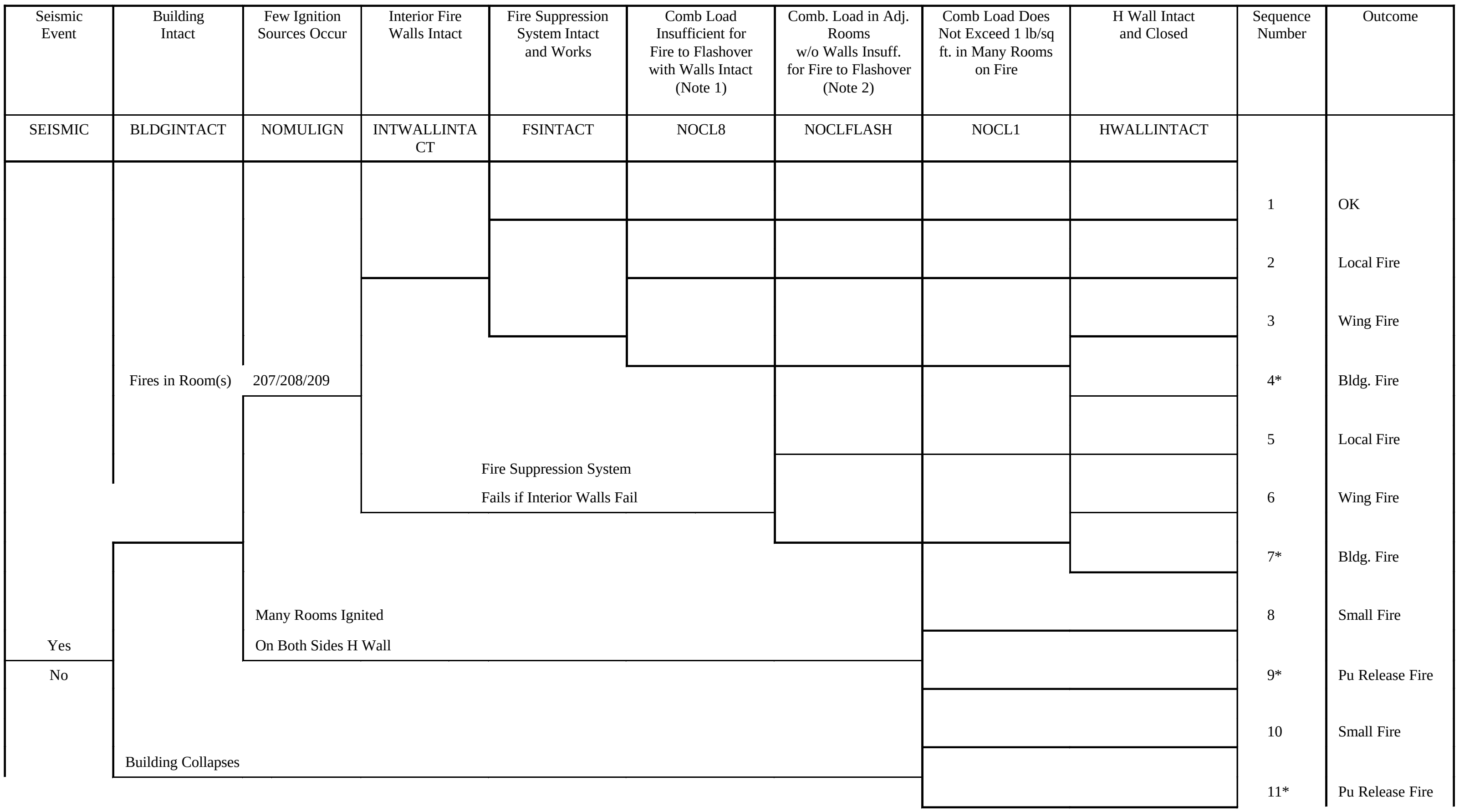
4.3.1. Event Trees.

Figure 4-2 displays the event tree used in this portion of the analysis. This event tree portrays the possibilities for the progression of a room fire due to a seismic initiating event. The event tree is structured so that the progression of the accident is represented in a time-ordered manner from left-to-right. In this model, successful mitigation of the room fire occurs whenever the building confinement remains intact.

The first event-tree heading (SEISMIC) represents the seismic initiating event. The next eight event-tree headings are used to denote the subsequent (post-initiator) status of PF-4 with regard to the building integrity, fire suppression availability, and type of fire.

The heading (BLDGINTACT), which occurs immediately after the initiating event, indicates whether the building remains intact or collapses. The next heading (NOMULIGN) is used to divide the ignition sources into one of two categories. A fire that is limited to one or more of the three Rooms 207, 208, or 209 represents one category of ignition source. The other category of ignition source involves many room fires on both sides of the H-wall because of failure of numerous low-fragility gloveboxes.

The next heading (INTWALLINTACT) represents the status of the interior fire walls. The subsequent heading (FSINTACT) is used to represent the availability of the fire suppression system. The following heading (NOCL8) indicates a decision as to whether the degree of combustible loading in the source room and any adjacent room exceeds 8 lb/ft^2.



Note 1: For a single fire: Comb Load < 8 lb/sq ft in both source and any adjacent room. For multiple fire: Comb Load < 36000 lb total in all rooms with fire.

Note 2: For a single fire in adjacent rooms with interior walls failed Comb Load <36,000 lb.

DEFINITION OF OUTCOME STATES:
OK: Fire Extinguished
For Fire Flashoever Scenariors:
Local Fire: Fire in a few rooms
Wing Fire: Fire throughout one wing
Bldg. Fire: Fire in entire Bldg., both sides H wall
For Scenarios involving many localized fires releasing Pu
Small Fire: Fires insufficient to release Pu

*Sequences that represent the release of bulk Pu

Fig. 4-2. Event tree used in seismic analysis.

Under the next heading (NOCLFLASH), a decision is made as to whether the total combustible loading in any set of adjoining rooms (assuming failure of interior fire walls) exceeds 36,000 lb. Yet another heading (NOCL1) is used to indicate a decision on whether the combustible loading exceeds 1 lb/ft^2 in each of many individual rooms that are on fire. Finally, the last split-fraction-related heading (HWALLINTACT) represents the status of the H-wall (intact or open).

The event tree has 11 sequences. Each of these sequences can be characterized by one of six possible end states or outcomes. The end state “OK” denotes that the fire is extinguished, confinement remains intact, and no plutonium is released. The end state “local fire” represents a fire that remains confined to a few rooms. In a “local fire” end state, the fire does not spread via flashover, confinement remains intact, and a release of plutonium is avoided. The end state “wing fire” represents a fire contained to one wing. In the “wing fire” end state, the fire does not spread via flashover to the entire building, confinement remains intact, and a release of plutonium is avoided.

A “building fire” end state represents a building-wide fire that has occurred from flashover and is assumed to result in confinement failure and release of plutonium. Finally, a “Pu release fire” end state denotes the release of plutonium from many simultaneous small fires. Here, the fire suppression system is not credited because it cannot extinguish numerous simultaneous fires. Confinement is assumed to have failed as a result of excessive ash loading on the ventilation filters.

Sequence 1 of the event tree represents an intact building structure with fires limited to at most Rooms 207, 208 and 209. Because the interior fire walls also remain intact and the fire suppression operates successfully, flashover is avoided, the building confinement remains intact, and no plutonium is released. This sequence has been assigned an end state status of “OK.”

Sequence 2 also represents an intact building structure with fires limited to at most Rooms 207, 208, and 209. Though the interior fire walls also remain intact, the fire suppression system fails. Because the combustible loading does not exceed 8 lb/ft^2 both in the source room(s) and in any adjacent room, flashover is avoided, the building confinement remains intact, and no plutonium is released. An end state status of “local fire” has been assigned to this sequence.

Sequences 3 and 4 are similar to Sequence 2, except that the combustible loading exceeds 8 lb/ft^2 in the source room(s) and an adjacent room. As a result, the fire is able to propagate into the remainder of the associated building wing. In Sequence 3, all interior fire pathways between wings (H-walls) are closed, and thus, fire propagation into the other wing via flashover is avoided. However, in Sequence 4, an open H-wall pathway is present, and the wing fire spreads into the remainder of the building. The building confinement remains intact in Sequence 3, whereas it fails in Sequence 4. Sequences 3 and 4 have been assigned end states of “wing fire” and “building fire,” respectively.

In Sequence 5, the building structure is intact with fires limited to at most rooms 207, 208 and 209. However, the PGA is sufficiently high to cause failure of the fire walls. Because the fire suppression system has a significantly lower fragility than the fire walls, it fails prior to failure of the fire walls.[17] The fire is contained within the room(s) of origin only because the total combined loading of combustibles in these rooms does not exceed 36,000 lbs. The building confinement remains intact, and no Pu is released. An end state status of “local fire” has been assigned to this sequence.

Sequences 6 and 7 are similar to Sequence 5, except that the total combined loading of combustibles in adjoining rooms (at least one of which is on fire) exceeds 36,000 lb. As a result, the fire is able to propagate into the remainder of the associated building wing. In Sequence 6, all interior fire pathways between wings (H-walls) are closed, thus preventing fire propagation into the other wing. The building confinement remains intact, and no plutonium is released. However, in Sequence 7, an open H-wall pathway is present, and the wing fire spreads into

[17] Even if the fire suppression system had a higher fragility than the fire walls, collapse of the fire walls would disable the fire suppression system

the remainder of the building. The building confinement is lost, and plutonium is released. Sequences 6 and 7 have been assigned end states of “wing fire” and “building fire,” respectively.

In Sequences 8 and 9, the building remains intact but with numerous room fires on both sides of the H-wall. The fire suppression system was not credited as it cannot extinguish many individual fires simultaneously. For Sequence 8, the combustible loading in the burning rooms does not exceed 1 lb/ft^2. As a result, these fires are incapable of releasing bulk plutonium. However, for Sequence 9, the combustible loading in the burning rooms exceeds 1 lb/ft^2, with the result that plutonium is released locally from each fire. Sequences 8 and 9 have been assigned end states of “small fire” and “Pu release fire,” respectively.

Finally, in Sequences 10 and 11, the building collapses as a result of the seismic event, and many fires erupt. Because the fire suppression system has a significantly lower fragility than the building structure, it fails prior to failure of the building.[18] In Sequence 10, the combustible loading in the burning rooms does not exceed 1 lb/ft^2. As a result, the fires are incapable of releasing bulk plutonium. However, for Sequence 11, the combustible loading in the burning rooms exceeds 1 lb/ft^2, with the result that plutonium is released locally from each fire. Sequences 10 and 11 have been assigned end states of “small fire” and “Pu release fire,” respectively.

In summary, Sequences 4, 7, 9, and 11 are the sequences that represent the release of bulk plutonium. As such, they are the sequences of interest in this analysis.

4.3.2. Fault Trees. Fault-tree models were developed to evaluate the probabilities for random failure of the fire suppression system and H-wall. These are the same fault trees used to support the operational (random) fire analysis and were described in Sec. 3.3.2.

4.4. Results and Discussions

In general, each of the seismic sequences of interest has a number of individual cut sets. To facilitate presentation and discussion of the results, the individual sequence cut sets were mapped into a smaller set of scenarios. Each scenario defines a unique combination of ignition sources and other types of failures necessary to result in a building-wide fire and release of bulk plutonium.

Table 4-2 summarizes a set of scenarios generated from the analysis. For each scenario, the table identifies the applicable event-tree sequence number, the scenario number, a brief description of the scenario, and pertinent comments and/or assumptions.

The final step in the analysis was to estimate the overall frequency of plutonium release represented by these scenarios. To partially correct for over-conservatism in the rare event approximation as previously discussed in Sec. 4.1.3, the initial set of scenarios in Table 4-2 was remapped into an updated set of scenarios. These updated scenarios account for common failure elements to facilitate use of the minimal cut set upper bound approximation, which is better estimate than the rare event approximation. These updated scenarios and their frequencies are summarized in Table 4-3.

There are two dominant scenarios, namely Scenario D and Scenario A. Scenario D, with a frequency of $5x10^{-6}$/yr, involves a total collapse of the building because of the seismic event. Many small fires are ignited from numerous internal/external (to building) sources. Scenario A, with a frequency of $4x10^{-6}$/yr, involves a seismic-induced fire that spreads throughout an entire wing as a result of failure of the fire suppression system or failure of the interior fire walls. Seismic-induced failure of the H-wall crossover dampers subsequently allows the fire to spread to the other wing, thereby resulting in a building-wide fire.

4.5. Conservatisms

A number of conservative assumptions were made in this analysis. Examples of some of these conservative assumptions are summarized below.

[18] Even if the fire suppression system had a higher fragility than the building structure, collapse of the building would disable the fire suppression system.

Table 4-2
Summary of Dominant Seismic Scenarios

Event-Tree Sequence Number	Scenario ID	Scenario Description (Important Elements in Each Scenario are Denoted by a Bullet)	Bounding Model Assumptions and Comments
4	4a	• Any one of eight ignition-source gloveboxes in Rooms 207/208 fails because of the seismic event and causes ignition (there are three ignition-source gloveboxes in Room 207 and 5 ignition-source gloveboxes in Room 208); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • The combustion load in Room 208 > 8 lb/ft^2 as a result of a random transient load; probability = $2.6x10^{-3}$ • Fire suppression fails because of seismic event; HCLPF 0.19 g • The H-wall opening fails as a result of seismic event; HCLPF 0.78 g	Many of the ignition-source gloveboxes will fail before the fire suppression system or H-wall because of their lower fragility (see data at left and in Table 4-1). Therefore, it is assumed that at least one ignition-source glovebox will fail, with ignition guaranteed in the associated room. In this scenario, the combustible loading in Room 208 happens to be > 8 lb/ft^2. Given that Room 207 already has a combustible loading > 8 lb/ft^2 and that the fire suppression system has failed, a fire in either room spreads to the other room and subsequently throughout the associated wing. Fire propagation to the other wing (a building-wide fire) occurs because the H-wall also has failed.
4	4b	• Any one of eight ignition-source gloveboxes in Rooms 207/208 fails because of the seismic event and causes ignition (there are three ignition-source gloveboxes in Room 207 and five ignition-source gloveboxes in Room 208); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • The combustion load in Room 208 > 8 lb/ft^2 because of a random transient load; probability = $2.6x10^{-3}$ • Fire suppression fails randomly; probability = $4.2x10^{-3}$ • The H-wall opening fails as a result of seismic event; HCLPF 0.78 g	*This scenario is the same as scenario 4a except that the fire suppression system fails randomly instead of from the seismic event.*
4	4c	• Any one of eight ignition-source gloveboxes in Rooms 207/208 fails because of the seismic event and causes ignition (there are three ignition-source gloveboxes in Room 207 and five ignition-source gloveboxes in Room 208); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • The combustion load in Room 208 > 8 lb/ft^2 because of random transient load; probability = $2.6x10^{-3}$ • Fire suppression fails because of seismic event; HCLPF 0.19 g • H-wall opening fails randomly; probability = $2.5x10^{-3}$	*This scenario is the same as scenario 4a except that the H-wall opening fails randomly instead of from the seismic event.*

Event-Tree Sequence Number	Scenario ID	Scenario Description (Important Elements in Each Scenario are Denoted by a Bullet)	Bounding Model Assumptions and Comments
4	4e	• One ignition-source glovebox in <u>each</u> of Rooms 207/208/209 fails because of the seismic event; (there are three ignition-source gloveboxes in Room 207, five ignition-source gloveboxes in Room 208, and four ignition-source gloveboxes in Room 209); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g. • Fire suppression fails because of the seismic event; HCLPF 0.19 g. • The H-wall opening fails because of the seismic event; HCLPF 0.78 g.	Many of the ignition-source gloveboxes in Rooms 207/208/209 will fail before the fire suppression system or H-wall because of their lower fragility (see the data at left and in Table 4-1). Therefore, it is assumed that an ignition-source glovebox failure will occur in each room, with ignition guaranteed in each room. The collective combustible loading in Rooms 207/208/209 exceeds 36,000 lb. Therefore, given a fire in each of these three rooms and failure of the fire suppression system, the fire spreads throughout the associated wing. Fire propagation to the other wing (a building-wide fire) occurs because the H-wall has also failed.
4	4f	• One ignition-source glovebox in <u>each</u> of Rooms 207/208/209 fails because of the seismic event; (there are three ignition-source gloveboxes in Room 207, five ignition-source gloveboxes in Room 208, and four ignition-source gloveboxes in Room 209); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • Fire suppression fails randomly; probability = $4.2x10^{-3}$ • H-wall opening fails because of the seismic event; HCLPF 0.78 g	*This scenario is the same as scenario 4e except that the fire suppression system fails randomly instead of from the seismic event.*
4	4g	• One ignition-source glovebox in <u>each</u> of Rooms 207/208/209 fails as a result of the seismic event; (there are three ignition-source gloveboxes in Room 207, five ignition-source gloveboxes in Room 208, and four ignition-source gloveboxes in Room 209); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • Fire suppression fails because of the seismic event; HCLPF 0.19g • The H-wall opening fails randomly; probability = $2.5x10^{-3}$	*This scenario is the same as scenario 4e except that the H-wall opening fails randomly instead of from the seismic event.*

Event-Tree Sequence Number	Scenario ID	Scenario Description (Important Elements in Each Scenario are Denoted by a Bullet)	Bounding Model Assumptions and Comments
7	7a	• Any one of 12 ignition-source gloveboxes in Rooms 207/208/209 fails as a result of the seismic event; (there are three ignition-source gloveboxes in Room 207, five ignition-source gloveboxes in Room 208, and four ignition-source gloveboxes in Room 209); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • Interior fire walls fail as a result of the seismic event; HCLPF 0.59 g • The H-wall opening fails because of the seismic event; HCLPF 0.78 g	Many of the ignition-source gloveboxes in Rooms 207/208/209 will fail before the interior fire walls or H-wall because of their lower fragility (see data at left and in Table 4-1). Therefore, it is assumed that an ignition-source glovebox failure will occur in at least one room, with ignition guaranteed in that room. Given failure of the interior fire walls, the fire spreads so that it includes all three rooms (207, 208, and 209). Because the fire suppression system has failed and because the collective combustible loading in Rooms 207/208/209 exceeds 36,000 lb, the fire spreads throughout the associated wing. Fire propagation to the other wing (a building-wide fire) occurs because the H-wall also has failed.
7	7b	• Any one of 12 ignition-source gloveboxes in Rooms 207/208/209 fails due to the seismic event. (There are three ignition-source gloveboxes in Room 207, five ignition-source gloveboxes in Room 208, and four ignition-source gloveboxes in Room 209); HCLPF values for most of these gloveboxes range from 0.08 g to 0.13 g • The interior fire walls fail as a result of the seismic event; HCLPF 0.59 g • The H-wall opening fails randomly; probability = 2.5×10^{-3}	*This scenario is the same as scenario 7a except that the H-wall opening fails randomly instead of from the seismic event.*
11	–	Total collapse of building; HCLPF = 0.77 g	Many small fires are ignited from numerous internal/external (to building) sources.

Table 4-3
Summary of Updated Scenarios and Frequency Estimates

Updated Scenarios ID	Set of Initial Scenarios Mapped Into Updated Scenario	Common Failure Elements in Initial Scenario	Frequency (per year)
A	4a, 4b, 4e, 4f, 7a	H-wall crossover dampers fail as a result of a seismic event (HCLPF = 0.78 g)	4.1×10^{-6}
B	4c, 4g	Fire suppression fails as a result of a seismic event (HCLPF = 0.19 g) and H-wall crossover dampers fail to close as a result of a random effects (probability = 2.5×10^{-3})	8.2×10^{-7}
C	7b	Interior fire walls fail as a result of a seismic event (HCLPF = 0.59) and H-wall crossover dampers fail to close as a result of a random effects (probability = 2.5×10^{-3})	3.3×10^{-8}
D	11	Building collapses as a result of a seismic event (HCLPF = 0.77)	5.4×10^{-6}

*The total frequency estimate of 9.5E-06 per year is slightly less that the sum of the frequency of the individual scenario because of the use of the minimal cut set upper bound refinement.

- It was assumed that all glovebox heat sources would be on immediately prior to a seismic event. No attempt was made to lower sequence frequencies by accounting for the fraction of time that glovebox heat sources are not in use.
- It was assumed that the fire spread would be independent of the operational status of the ventilation system.

5.0. CONCLUSIONS

Two categories of building-wide fires at FP-4 were evaluated. The first fire category, an operational fire, is initiated by a random fire that starts in or near a glovebox. The other fire category involves a secondary fire that is initiated by a severe seismic event. The analysis considered seismic initiating events over the entire hazard curve, including seismic events that exceed the beyond-evaluation-basis earthquake.

Propagation of a glovebox fire into a building-wide fire is estimated to occur with a point-value frequency of $4x10^{-10}$/yr. Stated differently, this type of accident scenario would be expected to occur about 1 time in every 2.5 billion years. The very low frequency of a building-wide fire is due to the availability of a number of barriers and mitigation features, including

- administrative controls on the amount of combustible material held in one location,
- an automatic fire water sprinkler system,
- fire walls that separate individual laboratory rooms and areas, and
- fire walls that separate the building wings.

There is one relatively high-probability event, namely, ignition source not extinguished by local worker response, which has a conditional probability 0.78. The product of the probabilistic data from of all these independent events (when also multiplied by a factor of 2 to account for fire initiation in either Room 207 or Room 208) is essentially the frequency of a building-wide fire because there is little sharing of SSCs among the constituent events in the sequence.

The analysis of a building-wide fire from a severe site-wide earthquake produced two dominant scenarios. The first involves a seismic-induced fire that spreads throughout an entire wing as a result of failure of the fire suppression system or interior fire walls. Seismic-induced failure of the H-wall crossover dampers subsequently allows the fire spread to the other wing. The frequency of this scenario is estimated to occur with a point value frequency of $4x10^{-6}$/yr. The second scenario involves the collapse of the building as a result of the seismic event. In this scenario, many small fires are ignited from numerous internal/external sources. The frequency of this scenario is estimated to occur with a point value frequency of $5x10^{-6}$/yr. Stated differently, these accidents would be expected to occur once every 500,000 yr.

These preceding frequency estimates for building-wide fires were based on conservative, bounding analyses. Even so, these results demonstrate that a building-wide fire is unlikely to occur during the life cycle of PF-4. A “best-estimate” analysis, if performed, would provide the basis for further judgment into the degree of conservatism inherent in the analysis assumptions. In turn, elimination or relaxation of conservative assumptions would reduce the point-value frequency estimates of a building-wide fire.

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